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CAPSTONE PROJECT REPORT

MINE SAFETY DETECTION SYSTEM (MSDS)

by

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(Cohort 311-1110 – Team B)

September 2012

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The search, detection, identification and assessment components of the U.S. Navy's organic modular in-stride Mine Countermeasure (MCM) Concept of Operations (CONOPS) have been evaluated for their effectiveness as part of a hypothetical exercise in response to the existence of sea mines placed in the sea lanes of the Strait of Hormuz. The current MCM CONOPS has been shown to be capable of supporting the mine search and detection effort component allocation needs by utilizing two Airborne Mine Countermeasure (AMCM) deployed systems. This adequacy assessment is tenuous. The CONOPS relies heavily upon the Sikorsky MH-60/S as the sole platform from which the systems operate. This reliance is further compounded by the fact both AMCM systems are not simultaneously compatible on board the MH-60/S. As such, resource availability will challenge the MCM CONOPS as well as the other missions for which the MH-60/S is intended. Additionally, the AMCM CONOPS systems are dependent upon the presence of warfighters in the helicopters above the minefield and as integral participants in the efforts to identify sea mines and to assess their threat level. Model Based System Engineering (MBSE) techniques have been combined with research and stakeholder inputs in an analysis that supports these assertions.m

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MINE SAFETY DETECTION SYSTEM

Cohort 311-1110 – Team B

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ABSTRACT

The search, detection, identification and assessment components of the U.S. Navy's organic modular in-stride Mine Countermeasure (MCM) Concept of Operations (CONOPS) have been evaluated for their effectiveness as part of a hypothetical exercise in response to the existence of sea mines placed in the sea lanes of the Strait of Hormuz. The current MCM CONOPS has been shown to be capable of supporting the mine search and detection effort component allocation needs by utilizing two Airborne Mine Countermeasure (AMCM) deployed systems. This adequacy assessment is tenuous. The CONOPS relies heavily upon the Sikorsky MH-60/S as the sole platform from which the systems operate. This reliance is further compounded by the fact both AMCM systems are not simultaneously compatible on board the MH-60/S. As such, resource availability will challenge the MCM CONOPS as well as the other missions for which the MH-60/S is intended. Additionally, the AMCM CONOPS systems are dependent upon the presence of warfighters in the helicopters above the minefield and as integral participants in the efforts to identify sea mines and to assess their threat level. Model Based System Engineering (MBSE) techniques have been combined with research and stakeholder inputs in an analysis that supports these assertions.

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LIST OF ACRONYMS AND ABBREVIATIONS

Acronym	Term
ALMDS	Airborne Laser-Mine Detection System
AMCM	Airborne Mine Countermeasure
AoA	Analysis of Alternatives
CSTRS	Carriage, Stream, Tow and Recovery System
CM	Configuration Management
CONOPS	Concept of Operations
DoD	Department of Defense
DOTMLPF	Doctrine/Organization/Training/Materiel/Leadership/Personnel/Facilities
DRM	Design Reference Mission
IPR	In Process Review
IPT	Integrated Product Team
KPP	Key Performance Parameter
LCS	Littoral Combat Ships
LIDAR	Light Detection and Ranging
M&S	Modeling and Simulation
MBSE	Model Based System Engineering
MCM	Mine Countermeasures
MCMV	Mine Countermeasures Vehicle
MDR	Mine Detection Ratio
MOE	Measure of Effectiveness

MOP	Measure of Performance
MSDS	Mine Safety Detection System
MSSE	Master of Science in Systems Engineering
NPS	Naval Postgraduate School
PEO	Program Executive Office
PMP	Project Management Plan
POC	Point of Contact
RMS	Remote Mine hunting System
SPR	Strategic Petroleum Reserve
STIL	Streak Tube Imaging Laser
ULCC	Ultra Large Crude Carrier
USN	United States Navy
UWIED	Under Water Improvised Explosive Devices
VLCC	Very Large Crude Carrier

EXECUTIVE SUMMARY

The USN and expeditionary Marine forces need an unmanned capability to rapidly and effectively locate mines and UWIED's in littoral waterways in a cost effective and timely manner that meets the following criteria:

- Must be organic and modularly integrated into the capabilities of the task force units in need of MCM.
- Must be able to get the war-fighter and expensive major assets out of the minefield during the MCM operations.

The results of this project provide a "fresh look" at the current CONOPS intended to be served by the MCM Mission Modules under development for the LCS. MBSE techniques were applied to vet the current CONOPS in response to the mission of searching for and detecting sea mines placed in the Strait of Hormuz.

From the fresh look, the following conclusions are presented.

- The Strait of Hormuz provides an ideal and relevant setting for the evaluation of the performance of an MCM CONOPS.
- Comparison of the search and detection functional requirements as derived from the Strait of Hormuz DRM to the U.S. Navy's current MCM CONOPS components reveals the CONOPS to be both resource and technology limited.
- MCM search, detection, identification, and threat assessment activities must be less reliant upon human operators as integral information processors.

The above conclusions support the larger conclusion that a new CONOPS employing a combination of the older MCM platforms in conjunction with the new AMCM systems could achieve the same results with less uncertainty. The current CONOPS requires 55 LCS hulls each equipped with two MH-60/S helicopters.

- LCS production delays could be augmented through the utilization of Arleigh Burke class destroyers or amphibious assault ships (i.e., LHAs or LHDs) assuming enough MH-60/S helicopters were available.
- The larger CH-53 helicopters deployed from LHAs and LHDs could perform a portion of the AMCM mission, if the MH-60/S helicopters were not available in sufficient quantities.

The report concludes with recommendations for future work.

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- Mr. Steve Johnson, Mine Warfare Doctrine Analyst, Naval Mine and Anti-Submarine Warfare Command

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I. INTRODUCTION/PROBLEM STATEMENT

The mine warfare Concept of Operations (CONOPS) currently employed by the United States Navy (USN) is in the process of being overhauled. The existing deployment of dedicated mine countermeasures (MCM) ships and equipment is intended to be replaced through the utilization of a new class of multi-mission ships equipped with two multipurpose helicopters (the Sikorsky SH-60/S). Additionally, the MCM detection equipment is being changed out from older mine hunting sonar (AN/AQS-24) to the still developmental AN/AQS-20A system. Lastly, a new technology has been developed to search for and detect untethered mines located at the surface and submerged at near surface depths for which the use of sonar is not effective. This CONOPS is currently in excess of fifteen years old since its inception; during that period, many of the planned MCM systems for both detecting and neutralizing have not materialized to support the modular mission format envisioned for the application of the Littoral Combat Ship (LCS) platforms.

Current geopolitical circumstances may dictate the practical need for MCM efforts by the U.S. Navy over the coming years, well in advance of implementing the modular LCS CONOPS. At present, the threat of Iran to mine the Strait of Hormuz (SoH) represents a very real and pressing example of the need outpacing our preparedness. This study is presented as an un-biased evaluation of the capabilities needed to perform the detection portion of MCM efforts. By utilizing a combination of Model Based Systems Engineering (MBSE) techniques to examine the mine detection combined with an independent outsiders' vantage, significant obstacles to the realization of the Navy's CONOPS have been found. These obstacles and the challenges that they pose are presented to the reader in the hopes that, through awareness of them, the Navy's CONOPS can be realized and utilized to meet the developing pressing needs

A. PROBLEM STATEMENT (PRIMITIVE NEED)

The United States Navy and expeditionary Marine forces need to locate and clear Mines and Under Water Improvised Explosive Devices (UWIEDs) from littoral areas both at home and abroad.

B. BOUNDED PROBLEM STATEMENT (EFFECTIVE NEED)

The USN and expeditionary Marine forces need an unmanned capability to rapidly and effectively locate mines and UWIED's in littoral waterways in a cost effective and timely manner that meets the following criteria:

- Must be organic and modularly integrated into the capabilities of the task force units in need of MCM.
- Must be able to get the war-fighter and expensive major assets out of the minefield during the MCM operations.

C. PROJECT OBJECTIVES

MBSE approaches will be utilized to explore the definition of a system capable of meeting the bounded need statement of providing an autonomous organic capability to U.S. Naval and Expeditionary forces operating within littoral waterways.

D. VALUE ADDED

The results of this project will provide a "fresh look" at the current CONOPS intended to be served by the MCM Mission Modules under development for the LCS. To perform the effort, modeling will be applied to vet the current CONOPS in response to the mission of searching for and detecting sea mines placed in the Strait of Hormuz. It is hoped that the DRM developed will be used and expanded to enable the Navy's MCM CONOPS effectiveness.

E. BACKGROUND AND RELEVANCY TO THE UNITED STATES INTERESTS

1. Current Status

Mine warfare in the USN is in a period of change, both in terms of operational concepts and in terms of development and fielding of assets. The USN is moving away

from a dedicated fleet of MCM vessels and helicopters towards an organic and modular concept of integrating MCM into the capabilities of task force units to provide in-stride mine countermeasures for theatre access and force protection in the littorals. Another major driver in the transformation is the intention to get the sailor and expensive major assets out of the minefield during MCM operations. (Jane's Underwater Warfare Systems posted 23–Nov–2009)

Currently, the USN operates an aging fleet of dedicated MCM Vessels (MCMV) of the Avenger Class. The MCMV have been augmented through the use of helicopter towed sonar systems deployed from amphibious assault aircraft carriers (LHD-3) as well as DDG class destroyers (DDG-91 forward).

In keeping with the stated criteria of the need statement above, "A major element in the USN's drive to provide in-stride MCM capabilities to task force assets is the development of an MCM package for the planned 55 Littoral Combat Ships optimized for operations near the shore in support of surface strike groups." (Jane's Underwater Warfare Systems posted 23-Nov-2009). The LCS mission modules are intended to employ Sikorsky MH-60/S Sea Hawk helicopter providing Airborne Mine Countermeasure (AMCM) capability by towing either the Raytheon AQS-20A or the Northrop Grumman AQs-24A towed mine hunting sonar.

The second criteria to get the warfighter out of the minefield during MCM operations was proposed to be answered by the WLD-1(V)1 Remote Mine hunting System (RMS) as a separate MCM mission package under development for use on the LCS platforms. The RMS is a diesel powered semi-submersible that tows the AQS-20 VDS to detect, localize and classify bottom mines and moored mines; the data gathered by the AQS-20A is relayed back to the parent vessel using line of sight or over the horizon real-time data links. The RMS system reliability has not met requirements (Director, Operational Test and Evaluation, 2008).

2. Historical Context

Following the Second World War, United States Naval Forces have suffered twenty attacks from five different methods of attack. The vast majority of the losses were due to mines and/or UWIED's. Figure 1 lays out by method of attack all the attacks on U.S. ships from WWII to 2000.

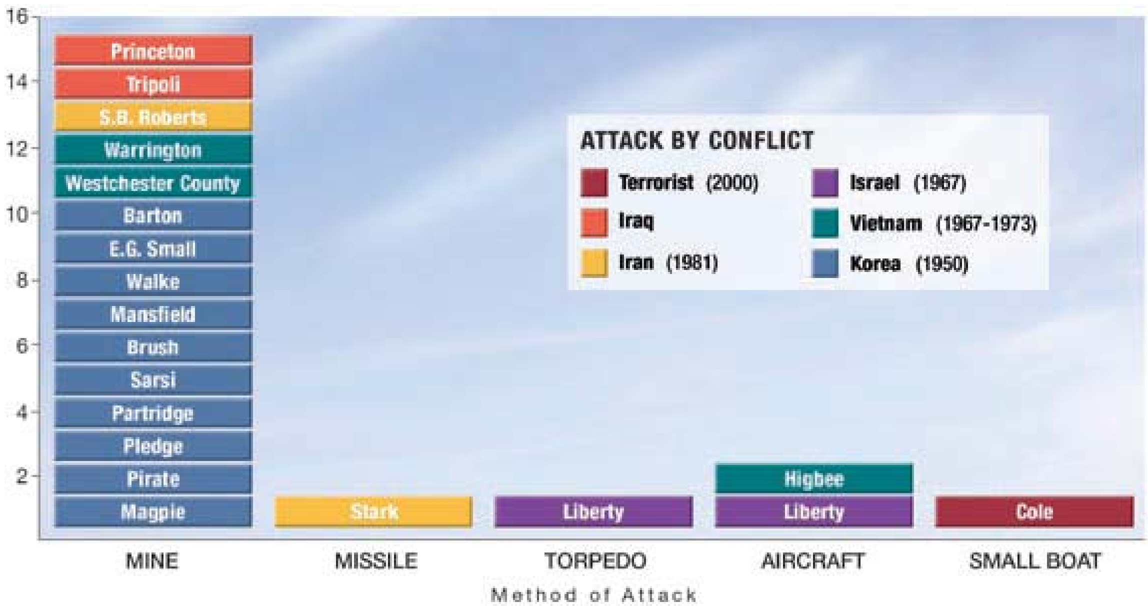

Figure 1. U.S. Ship Casualties, from (USNPEOLMW, 2009)

> …larger mines can be placed surreptitiously in channels and harbors to achieve spectacular effects-against, for example, the Staten Island Ferry, crammed with 2,500 commuters during and evening rush hour, or a cruise ship with four thousand vacationers and crew on board leaving Miami or Seattle. The tragedy of hundreds of bodies floating in a port would intensify the psychological message about the true security of America's home waters. (Truver 2008)

Truver (2008) also states that the economic impact to the United States and foreign trade markets could be substantial:

> Mines can directly attack the nation's waterborne trade. More than 90 percent of American exports and imports by volume transits U.S. ports, and the efficient and safe movement of our foreign, coastal, and inland-waters trades is critical for America's globalized, just-in-time, and just-enough economy. The economic consequences of just a few mines in our ports could be catastrophic, as the two-week West Coast labor slowdown

> in the fall of 2002 implies—a $1.95 billion impact per day. According to a University of California at Berkeley analysis, the direct and indirect economic impacts of a twenty-day longshoremen's work action would cost the U.S. economy more than $50 billion (in 2002 dollars). Even if no ships were sunk or damaged and no channels were blocked, explosions in a few key ports on East, Gulf, and West coasts and in the Saint Lawrence Seaway— clearly not an impossible feat, as September 11th tragically proved—would have a chilling effect on commercial shipping in terms of increased insurance costs and vessel lay days. The economic tremors would reverberate throughout the nation and to trading partners overseas. (Truver 2008)

The geopolitical potential for the use of mines and UWIED's is potentially limitless to rogue and terrorist nations intent on changing the current balance of power/influence both locally and globally. Potential regions of concern are shown in Figure 2.

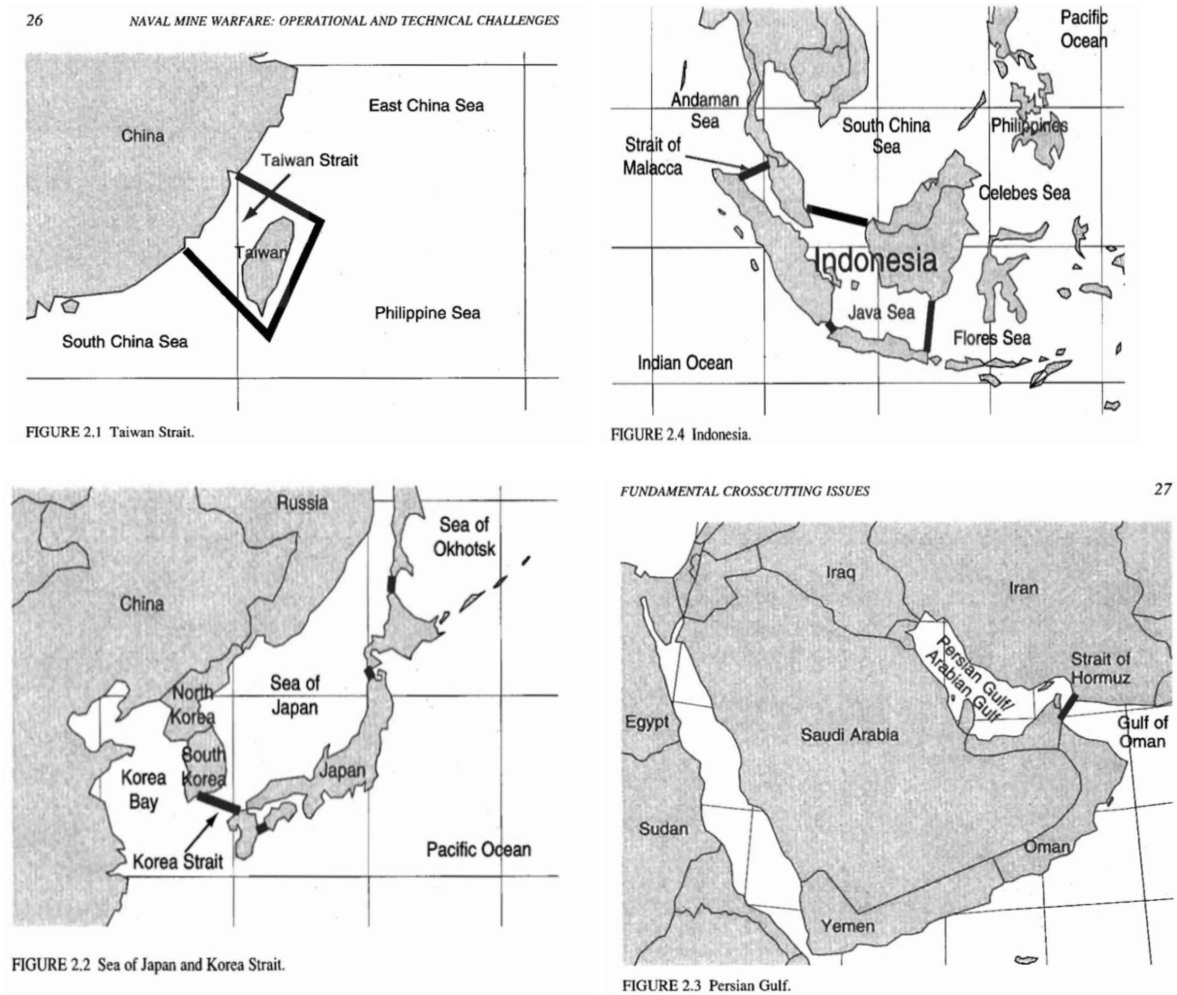

Figure 2. Potential regions of concern from (Naval Studies Board, 2001)

The Taiwan Strait represents an area that the Chinese have claimed as territorial waters; the use of mines and UWIEDs could effectively close the straight and enable Mainland China to effectively swallow (essentially annex) the island of Taiwan. The mining of the Korea Strait could isolate the key industrial South Korean city of Ulsan depriving an ally of needed resources. The Strait of Malacca is a major sea trade route; blocking it could result in significant global economic impact. Blocking the Strait of Malacca and the waterway between Singapore and the main island of Indonesia would force all shipping traffic through the Java, Celebes, and Flores Seas which have historically been stalking grounds for piracy. Lastly, and equally relevant for its' recent

history during the 1987 Tanker War, the Strait of Hormuz represents tremendous regional potential for the rogue nation of Iran to hold a large portion of the world's energy source hostage through the utilization of mines and UWIEDs.

The problems posed by mines and the means to meet the effective need are explored in the following pages of this report by applying system engineering principles and practices to define and then dissect, through decomposition, the mine search, detection, identification, and assessment activities of the larger MCM mission to create a requirements driven set of discrete functions against which to compare the current U.S. Navy's CONOPS components. This functional definition and dissection starts with a stakeholder analysis and description of sea mines and environmental conditions presented by the mission. The use of sea mines to close or disrupt oil tanker traffic through the Strait of Hormuz has been chosen as a Design Reference Mission. This high visibility scenario will be used as a stress test to generate functional requirements. By allocating the U.S. Navy's MCM CONOPS components to the DRM derived requirements, an operational analysis will be performed and conclusions/recommendations for the Navy's CONOPS and for follow on future work will be presented.

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II. SYSTEM ENGINEERING APPROACH AND PROBLEM DEFINITION

A. SYSTEM ENGINEERING OVERVIEW

System Engineering is the integration of design, manufacture, and maintenance of complex and multidisciplinary systems within evolving constraints. The system engineering process helps breakdown this undertaking to manageable levels, in a manner that combines best practices from management and engineering efforts. The structured, quantifiable approach to solving problems allows for a myriad of possible solutions and for all players to have input into both the synthesis and analysis of the effort.

The system engineering process is widely utilized and a number of philosophies have emerged to define this ever evolving methodology. However, most processes can be broken down into similar components: a requirements definition and analysis phase, a system design phase, an implementation and component testing phase, integration and system testing phase, and total system launch with performance assessment phase. For the Mine Safety Detection System (MSDS) project, the development of the left side of the VEE was the focus. The system engineering process was tailored to execute the Modeling and Simulation efforts ahead of Component Design and performed as the means by which System Analysis and Architecting were conducted. A recursive process was used to refine the system requirements, analysis, and architecture which further refined the modeling efforts. While the required capabilities for components were investigated; no component design was undertaken. The development of system requirements was conducted via research and stakeholder analyses. System analysis and System Architecting were performed through the utilization of functional decomposition and data processing models primarily using CORE and performance evaluation using Microsoft Excel. Although the Classic VEE shown in Figure 3 represents the entire system engineering process up through verification and validation along the right side of the VEE, the MSDS steps for the left side were iteratively verified and validated through the subsequent steps up to and through systems architecting.

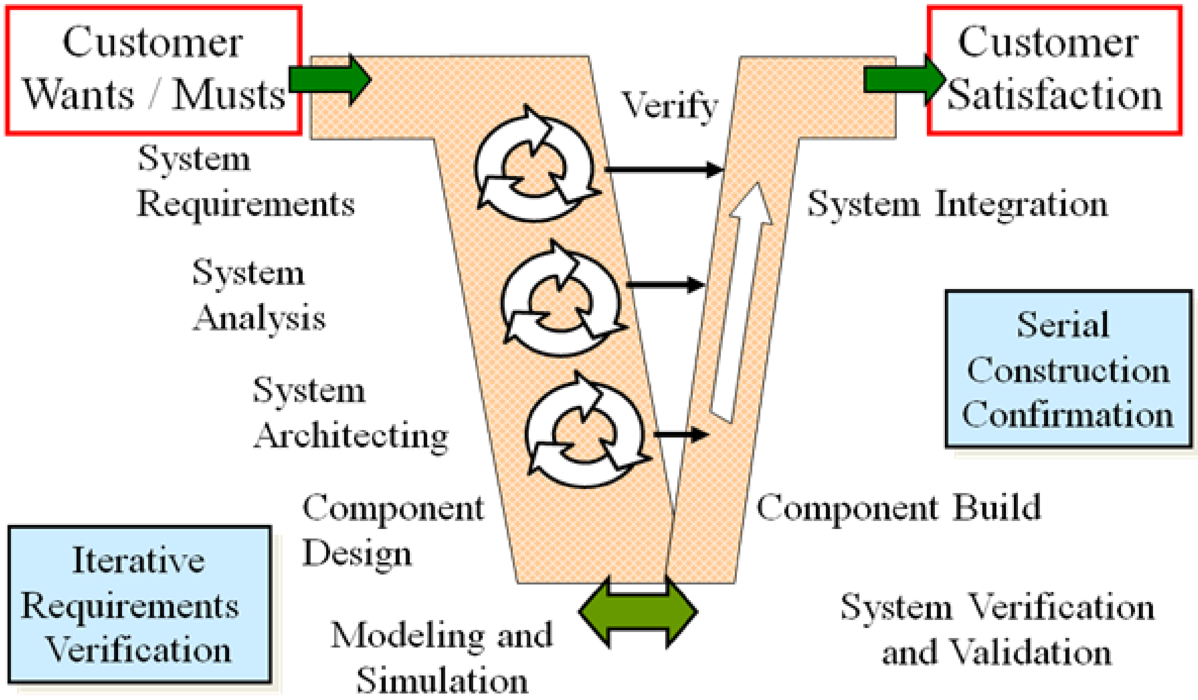

Figure 3. The Classic System Engineering VEE from (Muehlbach, 2012)

B. PROBLEM DEFINITION

1. Stakeholder Analysis

Efforts to address the issues associated with underwater mine detection have primarily been conducted by the USN. Many other entities are directly and indirectly affected by the presence and consequences of underwater mines. The entities are essentially stakeholders who have vested interests in the development of a solution to the problem. Table 1 and Table 2 divide the stakeholders into two groups; active and passive. Active indicates interaction by the stakeholder with the system during deployment and operation; passive indicates interaction outside of operation of the system but may provide guidance, information or requirements.

Stakeholder Role	Concerns
System Operator	System doesn't require much input as it is to be autonomous
	Is reliable/performing enough to save lives
	When operator input is required the system is easy to use
	System is safe to use
U.S. Navy	System cost for design, production, integration and maintenance is reasonable
	System is modular/adaptable to future platforms
	System has suitable performance
	System requirements
System Maintainers	System integrates with existing maintenance requirements, patterns and practices
	System does not add significant burden to existing maintenance procedures

Table 1. Active Stakeholders

Stakeholder Role	Concerns
Taxpayer	System has minimal cost and maximizes investment value
	System follows Government acquisition policies/guidance
	System performance is accountable/trackable (via metrics)
Program Manager/Executive Command	System has minimal impact on original mission load (is mostly autonomous)
	System reports status/health/state to centralized control
	Can be manually overridden
	Cost, Schedule and Performance
Intel Community	Accurate reporting
	System design follows well established security procedures
Joint Forces Command	System shares threats/possible impacts with external agencies
	System ingests threat/possible impacts tracked by other agencies
	System is interoperable with existing defense/tracking systems
System Trainers	System operation, installation and maintenance integrate into existing training regimen
	Existing training staff can teach system operation
	System documentation follows existing training standards
System Designers/Architects	There is sufficient data from stakeholders for developing requirements and proper system integration
	System design follows industry best practices
Contractors	Requirements are clearly defined and achievable
	Program remains funded throughout the development
System Evaluators	Requirements are testable/measurable

Table 2. Passive Stakeholders

2. Operational Resource Flow Diagrams

In order to understand what information each stakeholder inputs into the system and receives from the system an OV-2 or operational resource flow diagram was developed. This diagram depicts the high level information inputs and outputs for each passive and active stakeholder defined in Table 1 and Table 2. To delineate the two types of stakeholders Figure 4 depicts the active stakeholders in blue and the passive stakeholders in red. The information relative to each stakeholder is then depicted as blue for information input into the system and red for information output from the system to that specific stakeholder.

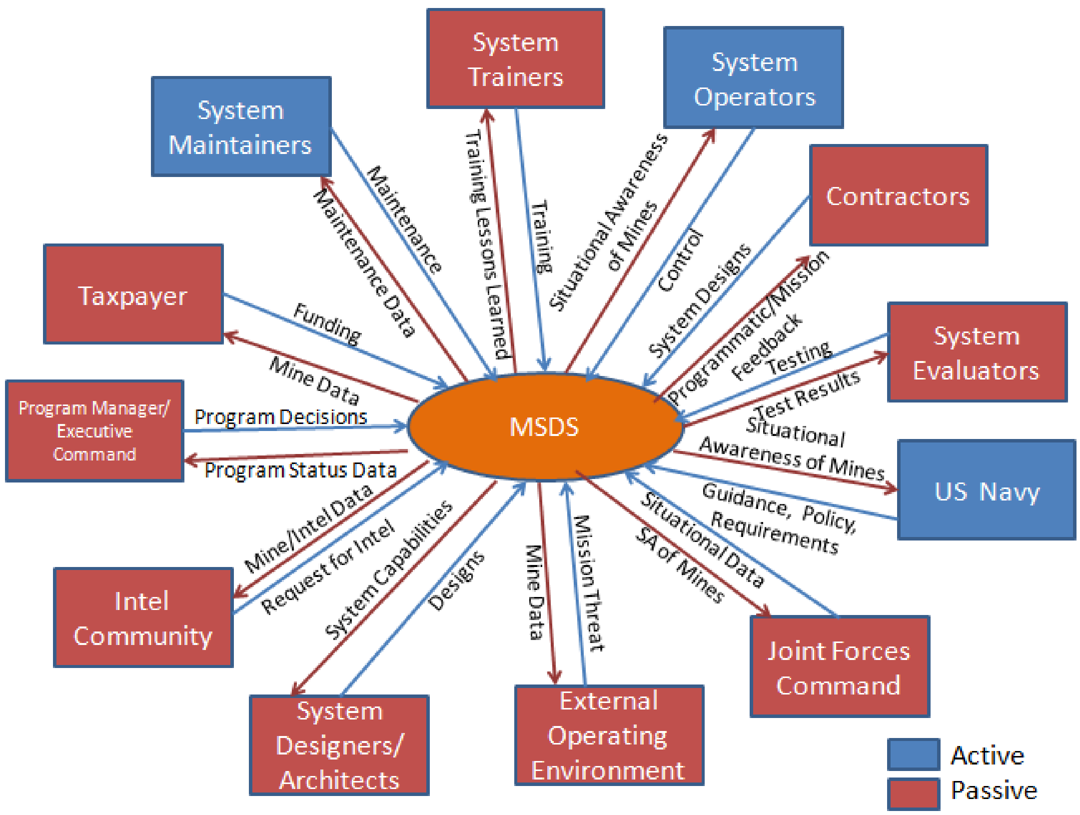

Figure 4. Operational Resource Flow Diagram

C. CONCEPT OF OPERATIONS

The MSDS will define a capability enabling the U.S. Navy to autonomously search, detect, track, identify, and report potential underwater mines. Additionally,

MSDS will seek to refine existing protocols and develop/define new capabilities with which underwater mines can be discovered more effectively without putting warfighters in harm's way. The Concept of Operations for MSDS is depicted graphically in Figure 5 OV-1.

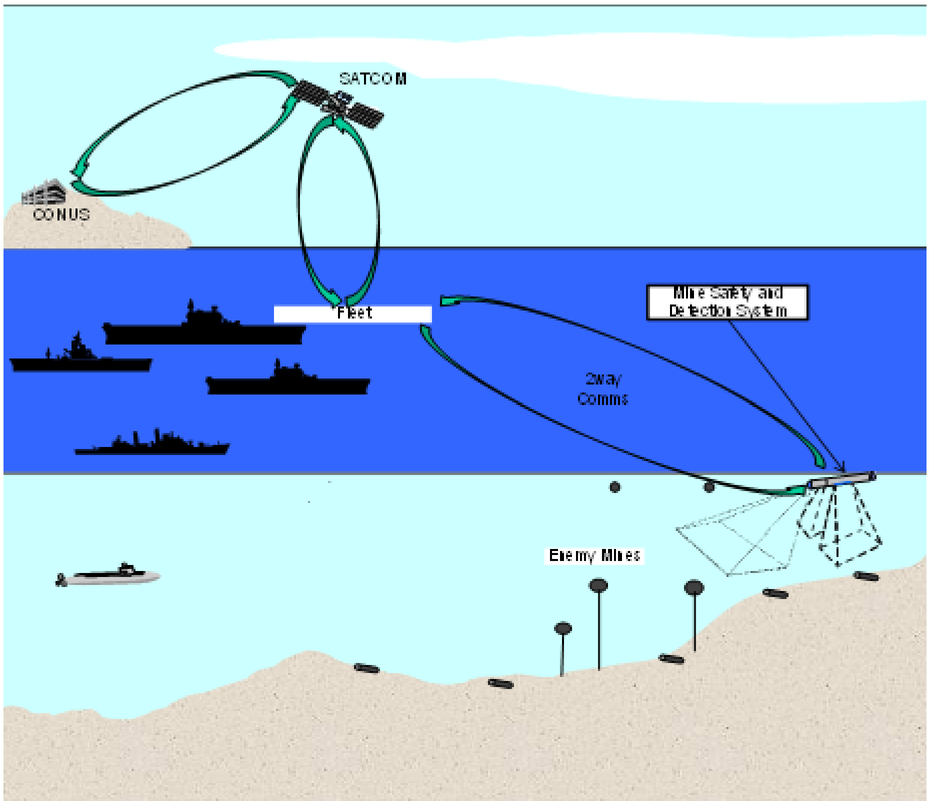

Figure 5. Operational View OV-1

The MSDS is shown as an autonomous vehicle searching for underwater mines and UWIEDs while actively in communication with external information sources shown as the USN Fleet. Mine threats are detected, tracked, identified and reported within MSDS protocol. MSDS will be a closed or bounded system that operates in an open and unbounded environment. The interfaces of the MSDS within the greater environment are restricted to be the threats (to include water hazards and underwater mines) and the information or data that describes them.

D. PROJECTED OPERATING ENVIRONMENT AND THREAT DEFINITION

1. Operating Environment

The MSDS is envisioned to be utilized in all navigable waters characterized by:

- depths from ten (10) meters to the open ocean (excess of 100 m)
- water temperatures as low as the sub-freezing arctic to equatorial values as high as 122 degrees Fahrenheit (approximately 50°C).
- water salinity ranging from fresh to brackish to open ocean salinity
- water clarity ranging from zero to unlimited visibility resulting from particulate suspension such as bottom sedimentation churning or biological content (plankton bloom or red tide)

The MSDS is additionally expected to operate successfully amidst levels of hostility from peaceful surveillance to open active aggression. While the MSDS will not possess any defensive capabilities, it will need to embody sufficient levels of survivability to insure successful mission performance.

2. Threat Definition

There are many types of mines and UWIEDs that can be characterized by the manner in which they are deployed, and by the mechanisms that they use to detect the target vessel and detonate. Deployment types are drifting, moored (at a fixed depth below the surface by an anchor cable from the ocean floor), bottom (resting on the sea floor), and buried (in the sea floor) as seen in Figure 6. Sensing and activation mechanisms (fuses) are classified as contacting and influence or proximity. Contacting fuses require physical contact between the fuse and the target vessel; these are the oldest types of mines that are still in use. Contact can be as simple as the depression of a mechanical switch or the change of electrical resistance of an electrically conducting cable. Influence fuses are designed to operate by detecting the presence of the target such as an increased magnetic field, the pressure wave caused by a ship passing above, or sound transmitted by a ships machinery or propeller cavitation. Influence fuses enable a mine to detonate near a target and essentially increase the effectiveness of the mine.

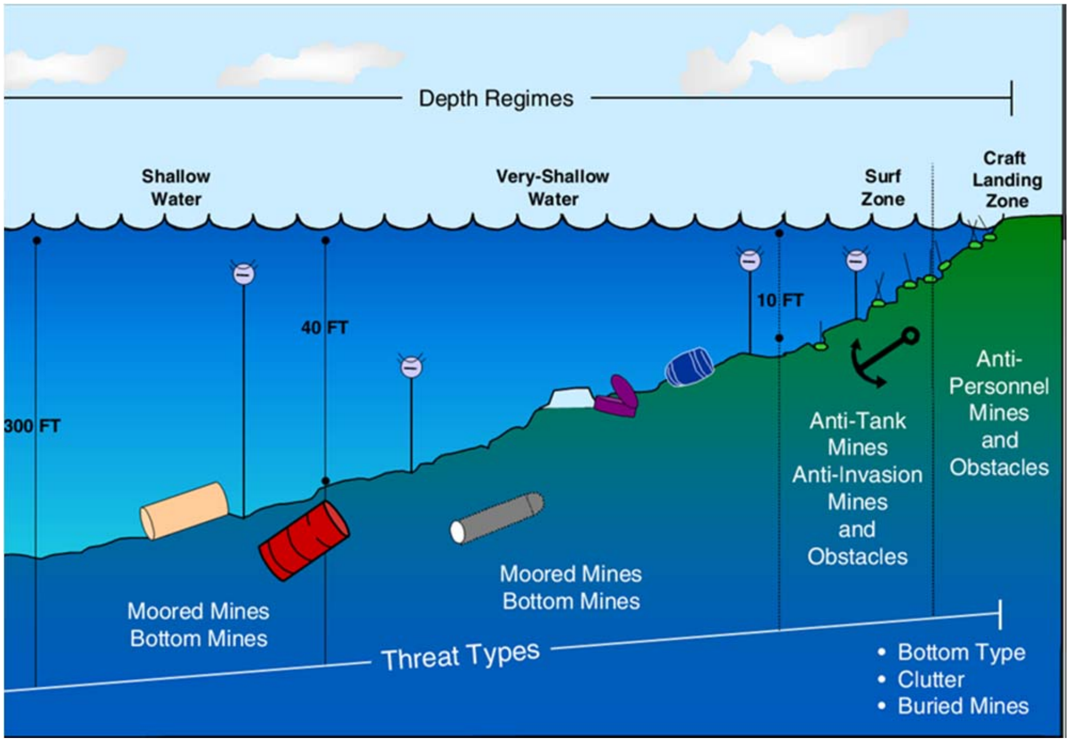

Figure 6. Mine Types after (U.S. General Accounting Office, 2001)

While many countries develop and manufacture sea mines, the majority of mines available for use by Iran, other rogue nations, or regional/international terrorist entities are largely based on designs originated by China and Russia. Russian influence mines have been characterized as having effective sensing ranges of up to 50 to 60m (Proshkin, 2001). Because a sea mine can only detonate if the fuse is activated the sensing range of the mine is considered to be the driving parameter of a mines' effectiveness. That is, even though the extent of damage caused by a mine depends primarily on the size of the explosive charge contained in the mines' casing, the most massive explosive charge within a sea mine is only as effective as the fuse mechanism that detonates it.

Due to their closeness to land masses, minimum and maximum depth of littoral waters are fairly uniform values but the bottom terrain can be considerably unique as demonstrated by the differences between dredged river bottoms and coral reefs. The environmental conditions that can be experienced in littoral waters represent an extremely wide range of temperature and water composition in terms of salinity and dissolved matter. The ranges in temperature largely correspond to the disparity between

polar and equatorial regions. Water composition differences can result from the influences of river in and outflows, tidal shifts, and bottom composition (gravel or silt) or seasonal influences such as red tide or plankton bloom. The sea mines employed, while fairly limited with regard to the types of deployment and the means by which they detonate, can be deployed specifically to exploit the specific nuances and unique combinations of environmental and water composition present to the area for which control is desired. Because this adaptability represents itself to the user of sea mines, every mine field can represent its own set of challenges to a mine-countermeasures effort. As a means to scope the nearly endless set on mine threats within the ocean environment, one setting is presented in the form of a design reference mission as described in the next section.

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III. DESIGN REFERENCE MISSION (DRM) AND MODELING

A. DESIGN REFERENCE MISSION (DRM)

A design reference mission is presented as a means to explore the effective need statement from the perspective of a hypothetical event for which mine detection would play a significant role. The Strait of Hormuz has been chosen from the four regions presented earlier in the introduction. The economic significance of the Strait of Hormuz to the U.S. and the rest of the world as demonstrated by its continued use as a setting for recent international conflict identify it as a setting for which an abundance of information exists. The DRM presented is, hopefully, as a fictitious problem set within a real physical location from which practical and actionable information can be gained.

1. Location: Strait of Hormuz

Crisis: In response to the enforcement of United Nations (UN) resolved economic sanctions by the United States and its allies, the Islamic Republic of Iran (Iran) has threatened to close the Strait of Hormuz to all shipping traffic and has claimed to have mined the shipping lanes defined by International Maritime Navigation Laws. Iran is targeting the oil tanker traffic through the strait as a means to retaliate in kind by depriving the rest of the world of up to 17 million barrels of crude oil per day or 35% of all of the world's seaborne traded oil (U.S Energy Information Admin., 2012).

Design Reference Mission: Search, detect, locate (depth and coordinates), identify (classify by deployment), and report all mines within as short of a time as possible. Data from the search will be utilized by others to clear the mines and open the sea lanes for oil tanker traffic.

Assigning a specific time target for the period which oil traffic must be restored is an extremely complex task that is dynamically driven by global demand supply chain considerations. As a buffer against oil supply instability and in response to past OPEC embargoes of the west, the U.S. maintains the Strategic Petroleum Reserve (SPR) which has a maximum capacity of 727 million barrels of crude oil (U.S. Department of Energy, 2012). Average U.S. consumption of Oil for the 2011 calendar year was approximately

20 million barrels per day of which approximately 14 million barrels were imported. The impact of oil traffic stoppage through the SOH could be partially mitigated through the use of regional pipe lines connecting to other sea routes for which transit times are longer to the CONUS and Asian markets (U.S Energy Information Admin., 2012). As such, the time window for which the strait could remain closed has not been specified with a minimum or maximum value.

2. Background

The tanker traffic through the strait is non-stop day and night via an average of 14 very large crude carriers (VLCC) in each direction. VLCC's are the world's second largest maritime cargo vessels second only to ultra large crude carriers (ULCC). The dimensions and basic information pertaining to all crude carriers are tabulated in Figure 7 by classification. The VLCC characteristics will be used as the definition of an oil tanker due to their commonality. Although ULCC's are the largest class of crude carrier, only two of the 12 ULCC's currently registered are operated as ocean tankers; the remainder are used as offshore waterborne storage containers. Additionally, U.S. Naval vessels operating in the Strait of Hormuz, while critical to the effort to open (and keep open) the sea lanes, do not possess sufficient draft or length as compared with global crude carriers. The target represented by the U.S.S. Nimitz, with the exception of its' beam, is relatively small in comparison as shown in Figure 18.

Class	Length	Beam	Draft	Overview
Coastal Tanker	205 m	29 m	16 m	Less than 50,000 dwt, mainly used for transportation of refined products (gasoline, gasoil).
Aframax	245 m	34 m	20 m	Approximately 80,000 dwt (Average Freight Rate Assessment).
Suezmax	285 m	45 m	23 m	Between 125,000 and 180,000 dwt, originally the maximum capacity of the Suez Canal.
VLCC	330 m	55 m	28 m	Very Large Crude Carrier. Up to around 320,000 dwt. Can be accommodated by the expanded dimensions of the Suez Canal. The most common length is in the range of 300 to 330 meters.
ULCC	415 m	63 m	35 m	Ultra Large Crude Carrier. Capacity exceeding 320,000 dwt. The largest tankers ever built have a deadweight of over 550,000 dwt.

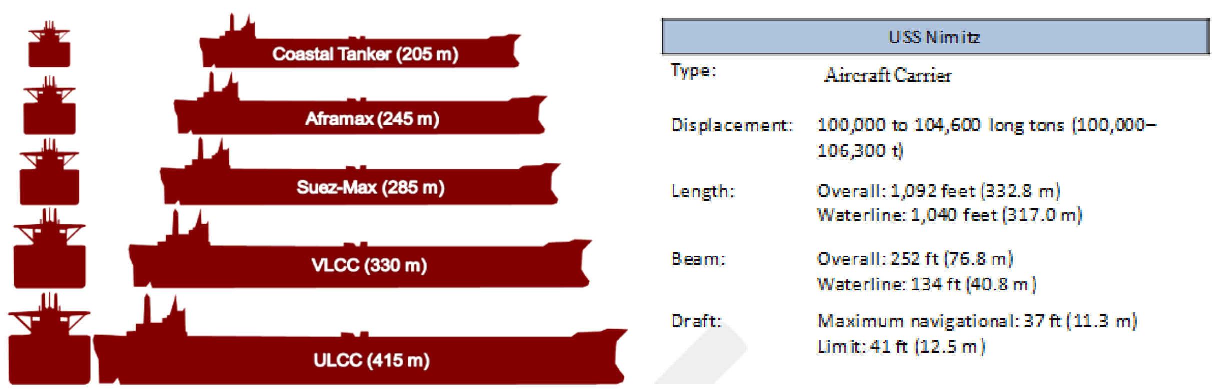

Figure 7. Tanker Class Comparison and USS Nimitz Data

Iran has demonstrated a willingness to use sea mines and is considered to possess a significant arsenal of Russian, Chinese, and North Korean made sea mines as well as their own produced copies. It has fostered trading partnerships with Russia, China, and North Korea since its inception in 1979 following the Islamic Revolution and deposition

of the Shah. In addition to a full array of sea mines, Iran has purchased and developed its own fleet of diesel electric submarines capable of operating within the Persian Gulf, the Strait of Hormuz, and the Gulf of Oman. It has the capability to lay mines nearly at will. Further, Iran has demonstrated a basic proficiency using sea mines as can be evidenced by U.S. losses in the 1987 Tanker War as well the denial of access of the Kuwaiti and Iranian ports during the first Gulf War.

The depth of the water in the sea lanes of the Strait of Hormuz is shown in

Figure 8 the low tide sounding chart; depth is in meters. The tidal swings from low tide in the strait (close to the equator) are less than 1 m and therefore considered negligible. The sounding chart shows the inbound sea lane, with a weighted average depth of approximately 73m, is shallower than the outbound lane for which the weighted average depth is approximately 83m. Additionally, the range of bottom depth is considerably more variable for the inbound lane (66m to 84m excluding an outside corner depth of 62m) than it is for the outbound lane (80m to 88m). The depth variation of the inbound lane shows contours or gradients that represent the equivalent of hills and valleys in which mines could be partially hidden. The bottom depth of the outbound lane is far more uniform. Lastly, the inbound sea lane directly borders Iranian waters for approximately on third of its length.

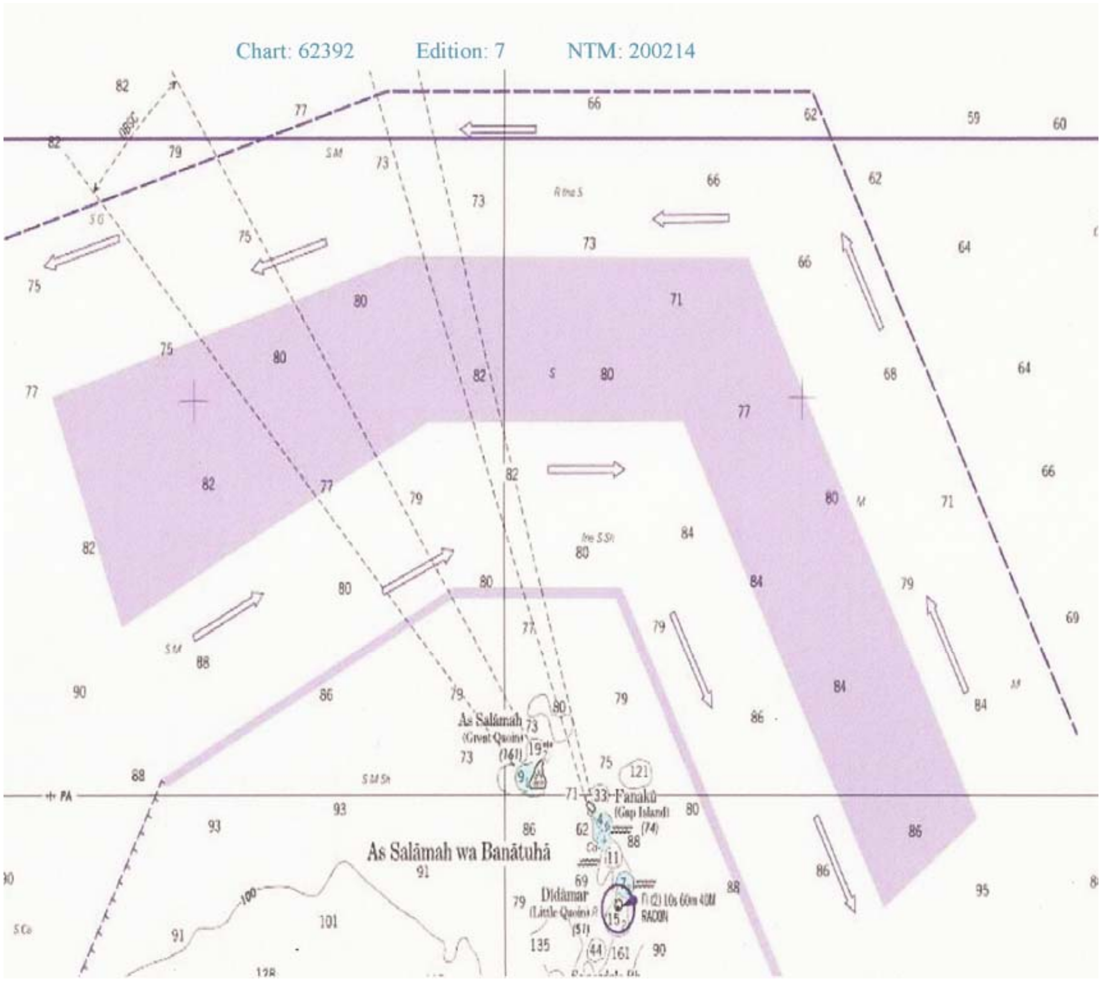

Figure 8. Strait of Hormuz depth chart after (OceanGrafix, 2012)

The flow of tanker traffic through the shipping lanes is strictly controlled as shown by the arrows in the sounding chart in

Figure 8. Inbound tankers (considered to be riding higher in the water due to their un-laden condition) operate in the shallower water. Outbound tankers, fully laden with approximately 1.2 million barrels of crude oil, navigate the deeper channel within Oman waters; these represent viable targets due to the combined results of economic loss of cargo and damage to the hull. The sinking of a tanker that comes to rest on the bottom in either sea lane will represent a navigation obstacle resulting in lane closure until the wreck can be cleared. Partial destruction of a sunken tanker should be strenuously

avoided as the addition of any debris on the floor of the sea lanes will complicate future mine detection efforts by creating sources for false positives and defilades for future mine deployment in wreckage.

3. Mine Field Composition

VLCCs draw 28m; this means that their 55m hull beam (width) by approximate 300m length rides 28m below the surface of the water. The maximum functional range for a bottom mine equipped with an influence fuse mechanism is approximately 60 m resulting in a maximum effective depth of 88m. The inbound sea lane with its' average depth of approximately 73m and maximum depth of 84m combined with the bottom contours of peaks and depressions represents an ideal environment for the deployment of bottom and buried mines because the bottom of the VLCC hull will pass well within the influence fuse range of a mine located at average depth.

Conversely, the outbound lane's average depth of approximately 83m combined with its' total depth variation of 80m to 88m makes it a possible but less than desirable environment for the use of bottom or buried mines; VLCCs will have to pass directly over the mine because the bottom depth is at or near the extreme range for which the influence fuses operate. Furthermore, the relative uniformity or lack of contours of the bottom depth in this lane makes it an unlikely location for the use of moored mines due to the probable ease with which moorings and objects suspended above the ocean floor could be detected. This sea lane is a likely application for the use of drifting mines because fully laden tankers are virtually incapable of emergency maneuvering to avoid detected mines near the surface that are essentially moving with the water's current. The influence fuse effective range combined with VLCC draft is shown graphically Figure 9 for the outbound sea lane.

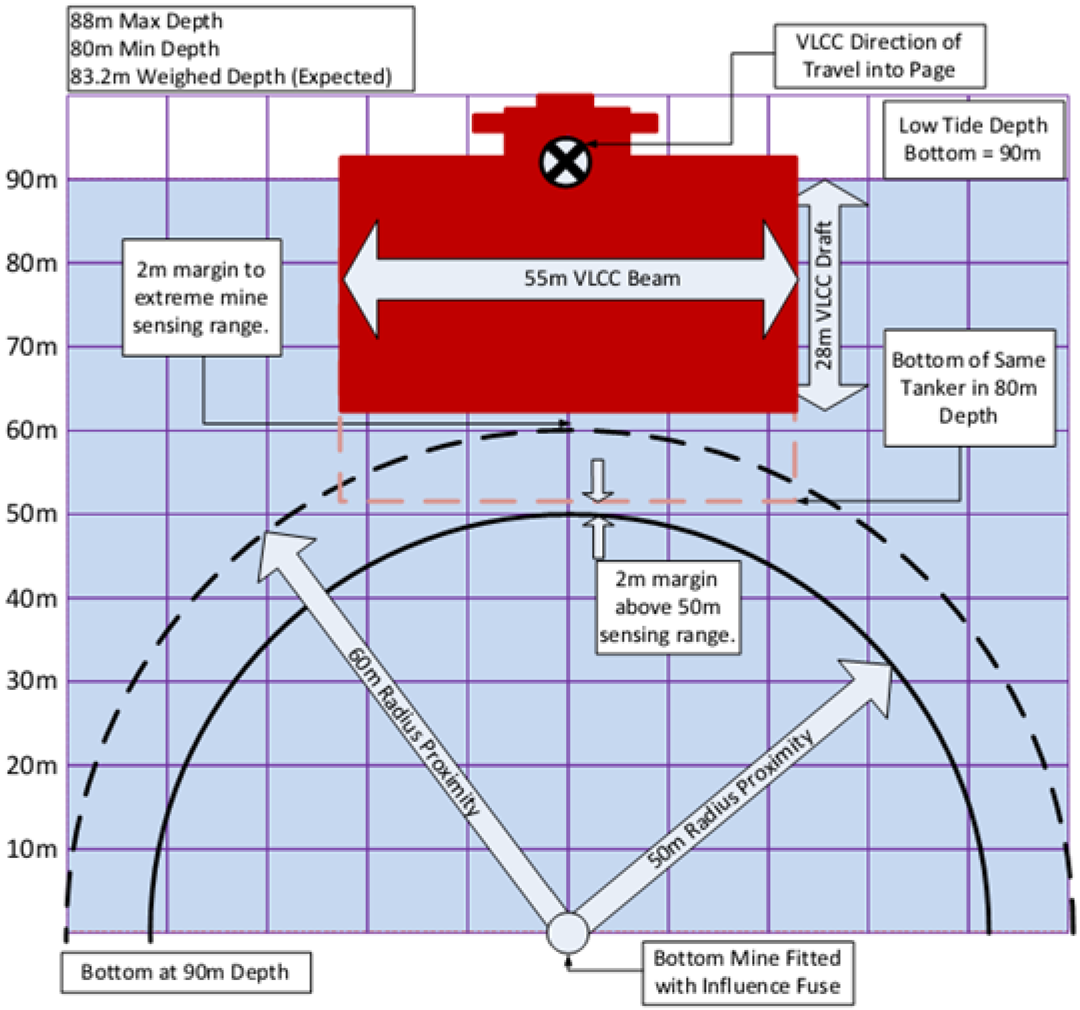

Figure 9. SOH Outbound Depth Comparison

Both sea lanes of the Strait as well as the center median are likely areas for the use of drifting mines. The utilization of drifting mines can be enhanced by the bidirectional nature of the current flow through the Strait between the Gulf of Oman and the Persian Gulf. Drifting mines that are placed into the outflowing tide on the Persian Gulf side of the Straight will flow out through the Straight toward the Gulf of Oman, and, can possibly reenter the Strait with the incoming tidal flow if undetected. If these mines are fitted with sea anchors, they may be capable of remaining in the Strait through tidal swings moving constantly between the inbound and outbound lanes through the un-trafficked median. Due to their unrestricted motion, drifting mines represent the largest single concern or threat to all outbound traffic.

4. Search Philosophy

Due to the probable deployment of mines based upon direction of traffic, bottom depth, and profile of the bottom, the Strait should be divided into three layers or search depth ranges: top (surface down to 30m), middle (30m down to 60m), and bottom (60m down to 90m or ocean floor if shallower).

The order in which the depth layers are searched follows a rational that emulates the analogy of "testing the waters before diving in". As the oil tankers are on the surface, the water (and thusly mines) closest to them is searched first. The further the search extends beyond the water through which the tankers navigate; the threat posed by mines should logically change. Direct navigation threats operating within the draft depth of the tankers require more looking outward than down. The middle represents an area in which threats are essentially all around. Lastly, the bottom layer search will primarily be defined by looking down at the bottom and objects very near it. This layered approach could enable the potential of sequentially opening of the Strait sea lanes to smaller class tankers (Coastal, Aframax, and Suezmax) at first and then expanding the size of the traffic allowed as the extent of the search and confidence of success increases.

First, both sea lanes and the median separating them need to be searched through the entire top layer. This is due to the concern for the use of drifting mines. Because targets will approach these mines essentially on a planar intercept path, the need is to maneuver a sensing device through this water by primarily looking (sensing) outward over the 30m depth from the surface rather than down. These devices can be conceptualized as explosive collision obstacles as they essentially occupy the same space through which the tankers navigate. The median area between the sea lanes must be searched as it could harbor a drifting mine that could enter either lane.

Next, the middle range of 30m down to 60m will be primarily populated by moored mines. As these are essentially fixed position mines, the need to search the median at this depth is not pressing in light of the requirement to search the sea lanes as

fast as possible. However, the immediate proximity of the median could be an ideal location for mines with influence fuses capable of "looking into" the inner parts of the inbound and outbound sea lanes.

Lastly, the bottom layer should be searched discriminately as follows. The inbound and outbound lanes should be searched for moored mines in a manner similar to the approach used for the middle region. Once both sea lanes are deemed to have been searched for moored mines suspended above the bottom, the bottom surface of the inbound lane must be thoroughly searched to identify bottom or buried mines by focusing on the shallowest depths and depth transitions first and the deeper and flatter areas as secondary. After the inbound lane is searched, the outbound lane bottom should be searched focusing on the shallower sections first and the deepest portions last.

The above sequence is based on the presumption that one search platform is utilized for each identified depth range. If multiple platforms were utilized or if depth ranges could be searched simultaneously, the sequence could be followed more expeditiously or multiple depth layers could be searched simultaneously or in parallel.

Current mine detection capabilities could utilize two separate technology based systems to search the full depth profile that exists within the sea lanes of the Strait of Hormuz; Light Imaging Detection and Ranging (LIDAR) is used for surface and near surface search of water depths of zero at the surface down to approximately 10 meters and mine hunting sonar systems are used for the remaining depths down to and including the ocean floor. Both systems are deployed and operate from airborne platforms. Conceivably, these two technologies would be applied sequentially and in a complimentary manner: LIDAR to detect and enable the clearing of any surface and near surface threats so that towed mine hunting sonar "fish" could operate freely in a look out and down manner with the confidence that the possibility of snagging or fowling its tow cable in contact with near surface mine tethers (both mine to mine and moored to the sea floor) has been removed. Because of the ease with which drifting mines could be placed into the Strait's currents from small submarines and disguised surface vessels during the towed sonar operation, continued use of LIDAR surveillance would be advised during the deeper water search efforts.

B. DESIGN REFERENCE MISSION (DRM) MODELING

Having presented and developed the DRM as a context for the utilization of a Mine Safety Detection System to search of the Strait of Hormuz for sea mines, the modeling of the search effort follows. Many technologies and solutions have been explored and developed to search for and detect the presence of sea mines. The modeling presented attempts to simulate the search of the Strait of Hormuz using active sonar as the detection technology. A brief discussion of the rationale employed to select active sonar follows.

The ships targeted by mines in these waters have been assumed to be commercial vessels. As such, the deployment methods for the use of sea mines have been assumed to be drifting, moored, and bottom; self-propelled or actively maneuvering mines such as dormant active torpedoes have not been considered. Buried mines represent special cases of bottom deployments for which a portion of the mine is exposed to the sea; they have been treated equivalently to bottom mines resting on the sea floor. These mines have further been assumed to be of the same basic size, shape and materials; anechoic or sound absorbing coatings are not considered.

Search/detection and Assessment/identification will have to be performed within the full volume of water from the surface to the bottom or sea floor. These efforts must be performed in all conditions of available light (both day/night and depth), particulate suspension (biological and sedimentation), and water temperature extremes of heat and cold to name a few. Additionally, the means by which the functions are performed must be reliable and capable of producing predictable and repeatable results to the extent that modeling and simulation of them could be performed. While many promising theoretical and experimental approaches are being developed, mature processes should be chosen whenever a choice exists.

With the basic assumption that all of the sea mines have the same essential properties regardless of the depth and means by which they are deployed and with a minimal set of criterion by which to evaluate potential solutions, several specific technologies were evaluated with respect to their individual applicability to conduct the

Search/Detect and Identify/Assess functions for/of sea mines. The technologies considered were radar, active sonar, passive sonar, infra-red (IR) thermal imaging, LIDAR (Light Detection and Ranging), and the use of marine mammals (dolphins and porpoises).

Radar (Radio Detection and Ranging) utilizes high frequency radio waves emitted from a source to bounce off of an object and return to the source from which the distance between the source and the object can be inferred from the time of travel in essentially the same manner that active sonar utilizes sound. Most radar systems utilize microwave transmissions which are readily absorbed by seawater rendering it useful over only very short ranges of feet as opposed to hundreds of meters prevalent in littoral waterways. Although efforts are on-going to solve this and other issues, the use of underwater radar systems is considered to be too experimental.

Sonar (Sound Navigation and Ranging) operates similarly to radar except that sound waves take the place of radio or microwaves. Sonar can be divided into two classes of passive and active.

Passive sonar consists of listening for or receiving sound energy waves that originate from other sources; because the sea mines of this evaluation are essentially inactive (as a source of sound energy) until they detonate, they will not produce any measurable sound source from which they can be detected. Additionally, because passive sonar requires listening, it is extremely susceptible to ambient noise interference from both active (intentional) and unintentional sources. As such, passive sonar has not been pursued as a viable technology solution.

Active sonar consists of transmitting sound source energy and receiving the return or reflection from objects in the water. Active sonar has seen extensive use in military, commercial, and scientific research environments as a means to both search large volumes of water and to identify objects both suspended in the water and resting on the ocean floor. The metallic materials used for basic sea mines make them very good reflectors of sound energy when compared to surrounding underwater naturally occurring substances. Additionally, the aforementioned extensive use of sonar makes it a reliable

and predictable technology from which to simulate and study its performance as part of a larger effort. A limitation of active sonar is its ineffectiveness at and near the water's surface; the boundary created by the water to air interface creates reflections that render a sonar system blind when looking up in close proximity to the waters' surface.

Infrared or thermal imaging technology works in much the same way that passive sonar does. In the case of IR, the heat that is radiated from an object is captured by a lens of a receiving device in the same way that a camera takes a photo. If IR could be used to provide visual data relating to mines, this information would support its use in the fulfillment of the Assess/identify functions. The problem or challenge to IR is that the ocean acts, generally, as a vast heat sink causing things that do not continually generate or dissipate heat energy to achieve thermal equilibrium (i.e., the same temperature as) with the water around them. As such, inanimate objects become essentially invisible within a short amount of time of submerged in the ocean. The metallic materials of mines conduct heat quite well; the time to achieve thermal equilibrium is relatively short. Lastly, IR methods generally tend to be associated with fairly high false alarm rates.

LIDAR (Light Imaging Detection and Ranging) represents a newly developing technology to find mines at or near the surface. A light source of blue-green laser energy is projected at the water surface from the air above; objects that are at the surface or suspended below the surface (near surface) are illuminated and reflect some of the laser light back to cameras near the source. The images captured are digitally stored and compared to reference data using analysis software and operator expertise. LIDAR, though relatively new and still developmental, provides a needed means to fill the surface and near surface water ineffectiveness of active sonar. The ability of LIDAR to capture images makes it well suited for the Assessment/identification functions for which inferences are made regarding the fusing mechanisms of a sea mine.

Sea mammal use for detecting mines has been shown to be very effective. The detection and location of bottom mines is a particular deployment method for which they have been extremely effective. Sea mammals (dolphin and porpoises) however, represent highly complex and extremely disparate individual solutions; i.e., mammals, as independent autonomous organisms, are difficult to replicate using a single model.

Further, the level of extent to which data can be transferred to and from sea mammals make them unique unlikely candidate choices to support the direction of the CONOPS away from dedicated or exotic resources. Lastly, the political notions with regard to the perceived endangerment or exploitation of animals are potentially toxic in todays' landscape. As such, the utilization of marine mammals has not been pursued.

Both active sonar and LIDAR together are needed to effectively search the waters of the sea lanes of the Strait of Hormuz and detect the presence of the mines deployed on the manner presented in the DRM discussion. Of these two, active sonar was chosen as the more suitable technology to model the search and detection functions. The limitations of active sonar's effectiveness on and near the surface are acknowledged; for these depths, the results obtained using active sonar are intended to be representative of those achieved using the developmental, newer technology of LIDAR. Additionally, the determination of a mine's type and operating mechanism (fuse) was modeled as a result of the observed location of the mine and the behavior of the mine in the water (i.e., water depth from surface and motion) rather than assessed from individual mine information as compared to a database. This simplification is a modeling convenience and is not intended to diminish the roles that identification and threat assessment perform for the broader effort. Lastly, all mines have been assumed to be fitted with influence rather than contact fusing mechanisms; this is a conservative treatment as the effective range of influence fuses exceeds contact mechanisms.

1. Building the Model

a. Data Sources

The source material for the model is based on the results from "Evaluation of the Performance of a Minehunting Sonar" (Thompson, 1997). It details mine detection performance or probability of detection (Pd) as a function of range from the sonar platform to the mine as shown in Figure 10.

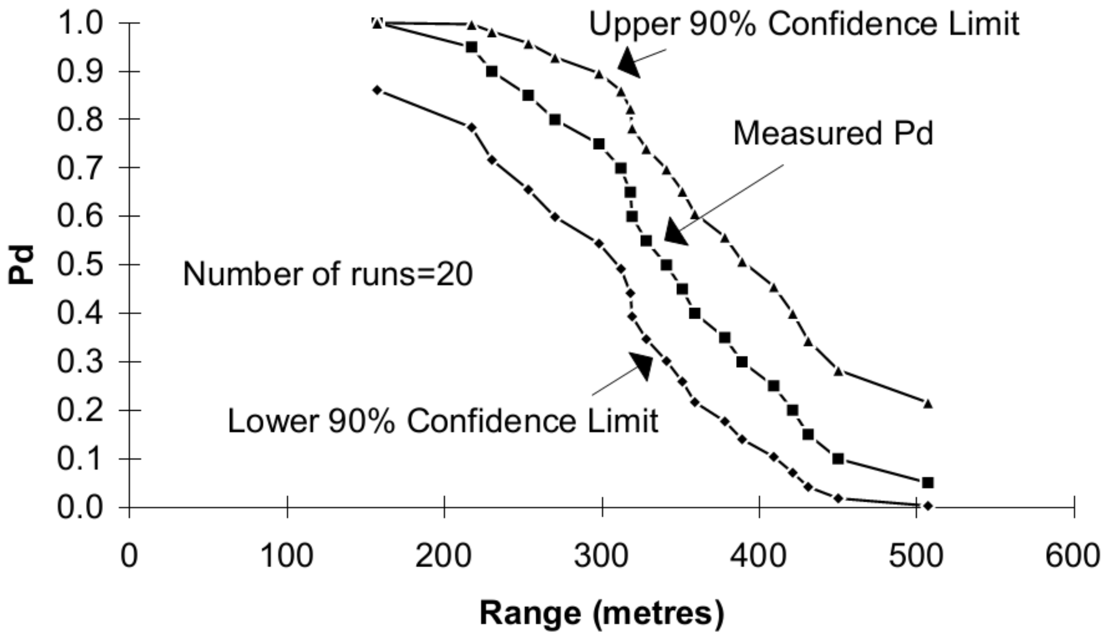

Figure 10. Typical Mine hunting sonar performance from (Thompson, 1997)

> ..it is apparent that the detection performance of a minehunting sonar fluctuates from ping-to-ping. Variations are also observed over longer periods and these variations occur even when the environment appears to be constant. Because the sonar performance fluctuates, the measurement of performance must be treated as a statistical sampling process. It is not sufficient to carry out a single detection run against a target and to use the detection range as a reliable indicator of sonar detection performance…The measure of detection performance used is that of probability of detection as a function of range. This is defined as the probability of detection by the time that the minehunter has closed the range from infinity to the given range. (Thompson, 1997)

Figure 10 shows the Pd at various ranges with twenty runs which produces the 90% confidence limit. Range is defined as the distance between the sensor and the mine.

b. Assumptions

The Pd for the DRM model is based on a table lookup for the values in Figure 10 which solely depend on:

- Sensor to mine range
- Number of passes of sensor over the minefield
- Goal: Overall Mine Detection Rate (MDR) = 95%

- Minimum desired confidence interval is 90%.

Factors or variables not included in the DRM model are:

- Bottom reverberation
- Noise level
- Propagation loss
- Target strength
- Operator
- Sonar surface conditions

Operational factors that were ignored for model simplicity:

- Transit time between SOH shipping lanes
- Gap between and around SOH shipping lanes
- Longevity or refueling of search vehicles

c. Mine Field Generation

The DRM model "minefield is populated … in a manner that gives a uniformly random distribution in both length and width" (Driels, 2004). The mine field dimensions and composition are found in Table 3. The depth of the entire minefield is based on the outbound shipping lane of the SOH which is deeper and the "worst case scenario". The width of the minefield is based on the shared width of the each of the SOH shipping lanes. The minefield length is based on the combined inbound and outbound shipping route lengths of the SOH.

Length (m) (in+out)	61,250
Width (m)	3,200
Depth (m)	88
# of Mines	500

Table 3. Minefield Composition

The probability of the type of mine deployed in the SOH is shown in Table 4 based on a uniform probability.

	Symbol	P(Deployed) Type of Mine
Drifting	D	0.2
Moored	M	0.5
Bottom	B	0.3

Table 4. Mine type uniform probability of deployment

Once the type of mine is chosen the depth is chosen. The bottom mines will obviously be on the sea floor (88m). The drifting and moored mines are uniformly distributed according to their depth boundaries shown in Table 5.

Mine Type Min/Max Depth	Meters
Drifting min depth	0
Drifting max depth	10
Moored Min Depth	20
Moored Max Depth	60

Table 5. Drifting and moored mine depth boundaries

2. DRM Modeling Results

The width of each individual shipping lane of the SOH is much wider or off the chart for sonar range in Figure 10. Half the SOH shipping lane is 1,600m, but the maximum sonar detection range in Figure 10 is just over 500m with a Pd of less than 10%.

Figure 11 shows the poor search results that would result from using a single search vehicular with an overall detection rate of 24%. (Table 6). It also shows the randomly uniform distribution of the mines with the minefield as well as the path of the sensor. As expected the undetected mines are located on the outer edge of the minefield. Pd is based on the range between the mine and the sensor. A table look up is performed for the range based on binomial distribution from Figure 10. Since most of the ranges do not have an exact match from Figure 10 a linear approximation is made for Pd from the two closest range points.

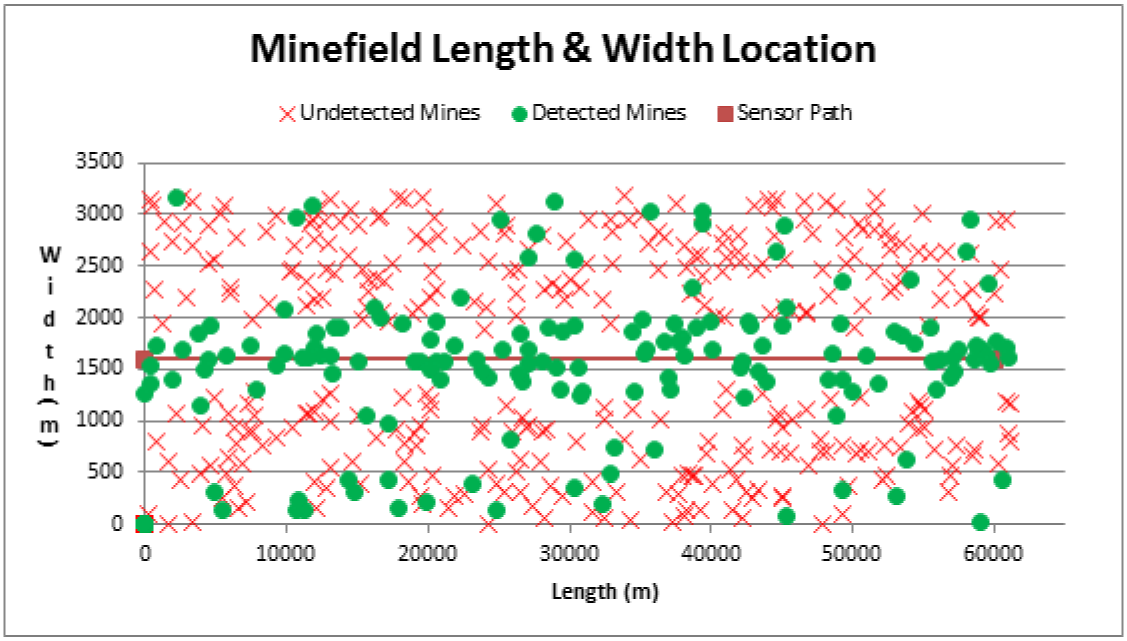

Figure 11. Single Minefield length & width location (Green Circles Detected/Red X's Undetected)

General types of mines based on deployment method:

- Drifting – floating mines at/near the surface of the water
- Moored – mines that are anchored/weighted to the sea floor at various levels
- Bottom – mines found resting or buried on the sea floor

	Symbol	P(Deployed) Mine of Type	Average Depth	Deployed	# Mine Detected	% Detected MDR
Drifting	D	0.2	5.2	107	27	25%
Moored	M	0.5	39.7	252	62	25%
Bottom	B	0.3	88.0	141	31	22%
Totals	na	1	na	500	120	24%

Table 6. Single Sensor Mine detection Summary

To increase the MDR additional sensors or MCM vehicles were added to the model. A minimum of five sensors platforms were required to simultaneously sweep the SOH to achieve the 95% MDR goal.

Figure 12 is a “top down” view of the combined shipping lanes. It shows the sensor platforms evenly spaced across the width of the SOH. The majority of the undetected mines (red X’s) are on the outside of the shipping lanes. This is the result of the edges not have the mutual sensor coverage enjoyed by the areas between two sensors. The location of the sensors as they pass through the shipping lanes is listed in Table 7.

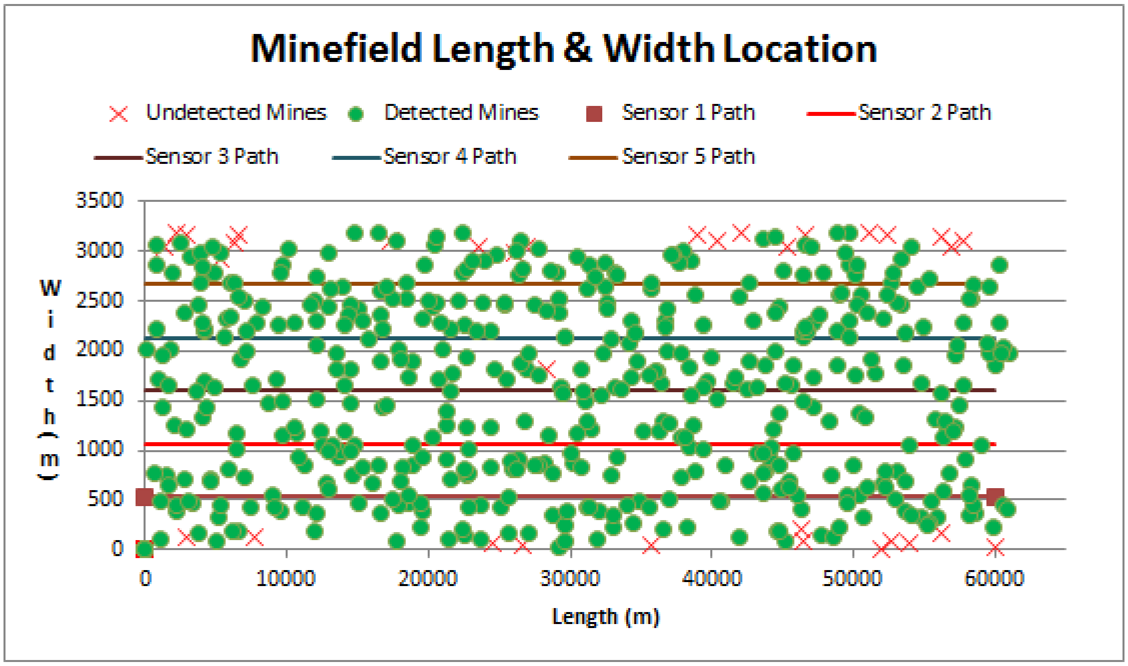

Figure 12. Five Sensor Minefield Distribution Across the Width of the SOH (Green Circles Detected/Red X’s Undetected)

Note the model ignores surface conditions for active sonar for simplicity of the model.

	Depth of Sensor (m)	Loc_W (m)
Sensor 1	0	533
Sensor 2	0	1067
Sensor 3	0	1600
Sensor 4	0	2133
Sensor 5	0	2667

Table 7. Sensor Location in Shipping Lane (Depth & Width)

Figure 13 is a cross section of the shipping lanes or a “side view”. No noticeable pattern is seen based solely on mine depth.

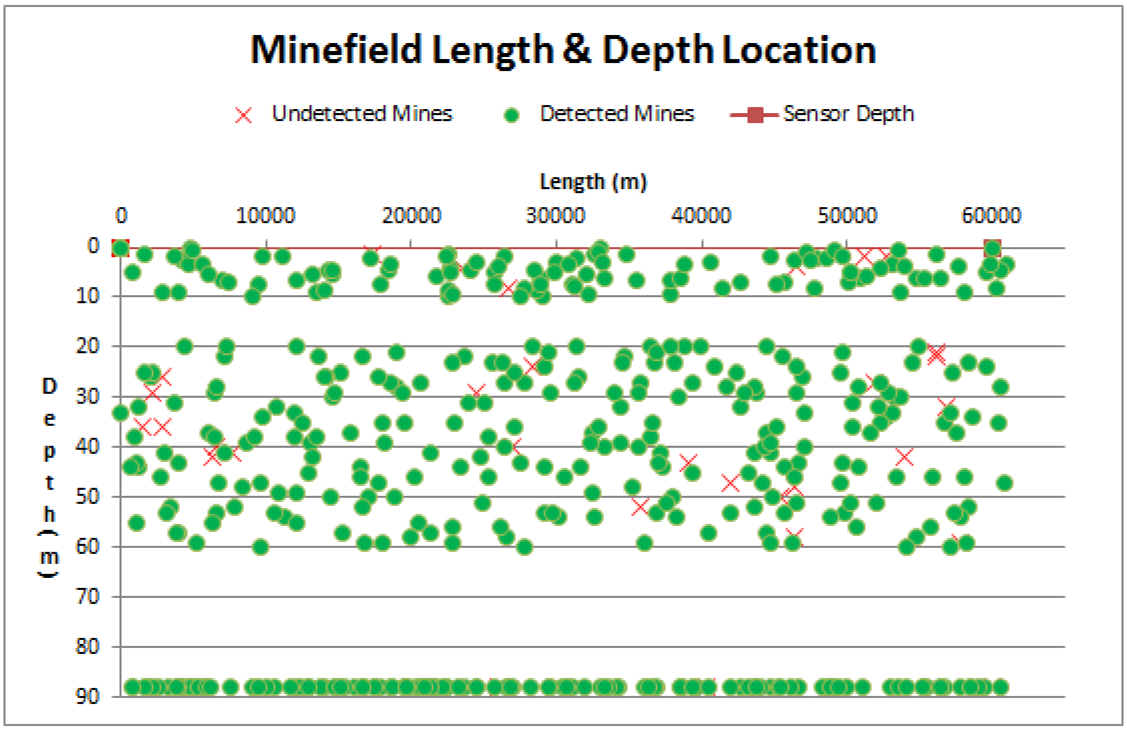

Figure 13. Five Sensor Minefield length & Depth Location (Green Circles Detected/Red X’s Undetected)

Figure 14 shows the distance between the mine and the closes sensor vs. the depth of the mine. Due to the positioning of the sensors in the mine field most mines are within

300m of any given sensor. As expected the undetected mines are most highly concentrated at the greatest distances with bottom mines tending to be the farthest away from the sensors.

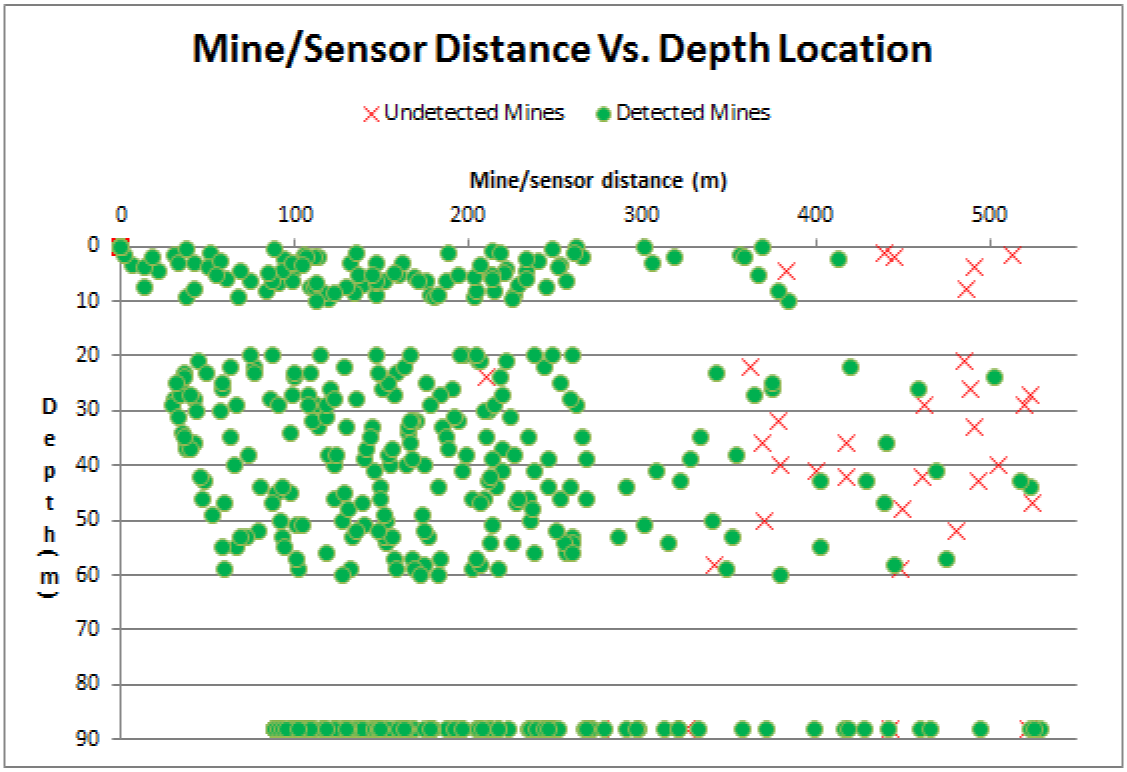

Figure 14. Five Sensor Mine/Sensor Distance vs. Depth Location (Green Circles Detected/Red X's Undetected)

	Symbol	P(Deployed) Mine of Type	Average Depth	Deployed	# Mine Detected	% Detected (MDR)
Drifting	D	0.2	5.2	87	85	98%
Moored	M	0.5	41.9	255	243	95%
Bottom	B	0.3	88.0	158	148	94%
Totals	na	1	na	500	476	95%

Table 8. Five Sensor Mine detection Summary

Table 8 shows the improved results using 5 vehicles to scan the SOH. The variation of detection rates between drifting, moored and bottom mines can be explained by their increasing distance from the surface riding MCM detection vehicles and sensors. Overall a MDR of 95% with a 90% confidence interval was achieved using 5 vehicles each doing 20 passes.

3. DRM Time to Search

A high MDR is not the only constraint. MCM operations in the SOH need to be performed in a timely fashion to open the straight to commercial oil traffic and US Naval ships.

Equation 1 shows the basic calculation for each individual vehicular to travel through both shipping lanes. Note that the transit time between the inbound and outbound lanes is ignored as well as any refueling requirements.

$$SearchTime = \frac{Length}{Velocity} * NumberOfRuns$$

Equation 1: Search Time

For an autonomous underwater vehicular (AUV) with an average maximum sustained speed of 2 knots or 1.028m/s the search time for the SOH with a single vehicular is 330 hours or 13.7 days. This same search time applies to five search vehicles model example since the vehicles would be searching in parallel. The search time could be halved by doubling the number of search vehicles. This would allow you to search both shipping lanes at the same time and avoid lane-to-lane transit times.

Vehicle Type	**Max Search Velocity**		**Mine Field Length**	**Number of Runs**	**Search Time (5 vehicles)**		**Search Time (10 vehicles)**	
	Knots	M/S	Km	#	Hours	Days	Hours	Days
UAV	2	1.03	61.25	20	330.7	13.8	165.4	6.9
Towed	10	5.14	61.25	20	66.1	2.8	33.1	1.4

Table 9. SOH Search Time Summary

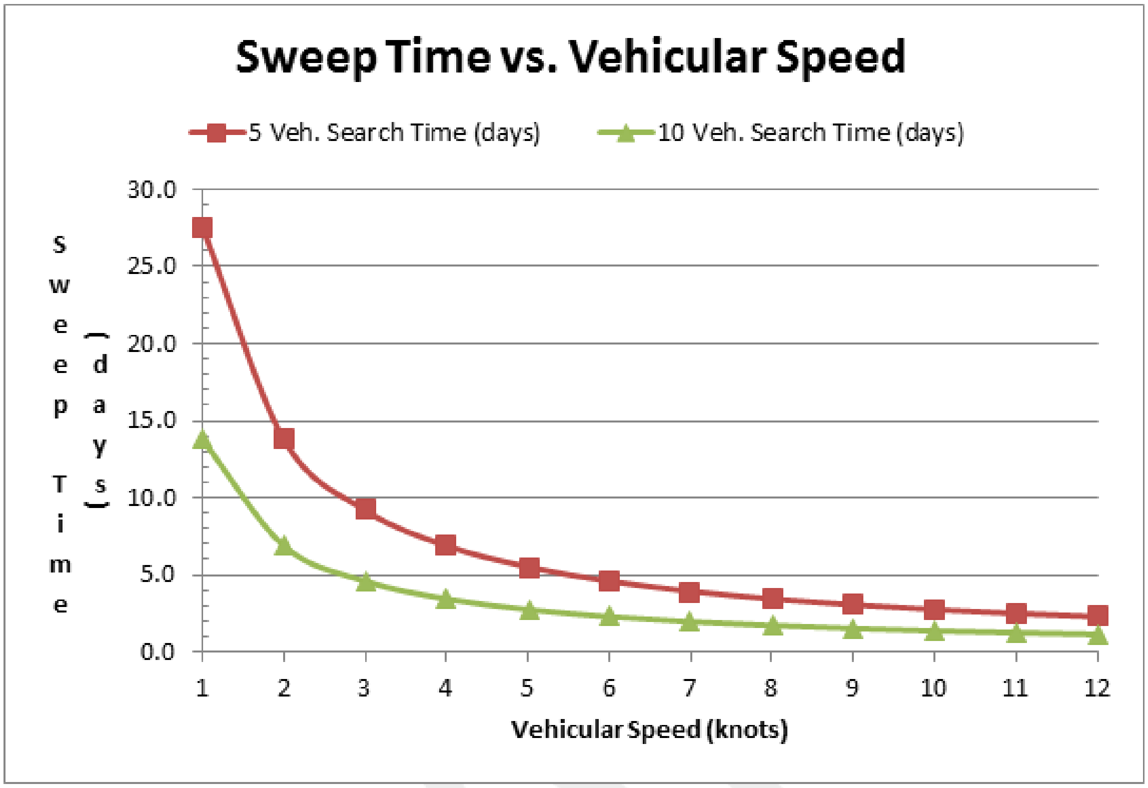

Figure 15. Sweep Time vs. Vehicular Speed

For a sensor platform being towed by an aerial vehicular with an average maximum sustained speed of 10 knots or 5.14m/s the search time for the SOH with a single vehicular is 66.1 hours or 2.76 days. A summary of the SOH search times can be found in Table 9 and the overall effect of the vehicular speed on the total sweep time for the SOH can be found in Figure 15.

The DRM has been used to evaluate the use of active sonar to search for mines deployed to disrupt commercial vessel traffic in specific environmental conditions. The insights gained will now be applied to develop the requirements the MSDS must satisfy. The requirements will then be transformed into functions needed to satisfy them. Assessment of the current Navy MCM CONOPS will be determined by comparing its component solution functions to the set derived from the DRM.

IV. REQUIREMENTS, FUNCTIONAL ANALYSIS AND ARCHITECTURE

A. REQUIREMENTS SUMMARY

The requirements for the MSDS have been identified at the system level and are identified in Table 10. The requirements for the MSDS were derived from mine hunting capability research, DRM modeling and evaluation of stakeholder requirements. Many different types of requirements have been identified, to include functional requirements, physical requirements, environmental requirements, suitability requirements, and interoperability requirements.

ID	Requirement Name	Requirement
REQ.0	System Requirements	These are the requirements for the system architecture. The higher level requirements trace back to the capabilities. Requirements are decomposed from high level solution-neutral capabilities and requirements all the way down to solution-oriented system specifications.
REQ.1	Search/Detect	The system shall be able to search and detect different types of underwater mines, drifting, moored, bottom/buried.
REQ.1.1	Search Sensing	The system shall have a search area of xx cubic meters
REQ.1.1.1	Searching Speed	The system shall be capable of performing a search moving at speeds greater than or equal to yy m/sec.
REQ.1.2	Detect	The system shall detect different types of underwater mines, drifting, moored, bottom/buried.
REQ.1.2.1	Mine Location	The system shall be capable of locating a mine within a volume of 8 cubic meters
REQ.1.2.2	Mine Depth	The System shall determine a mine's depth in water within 2 m (i.e., +/- 1m)

ID	Requirement Name	Requirement
REQ.1.2.3	Mine Coordinates	The system shall fix the position of fixed position mines (i.e., bottom and moored) within 6 cubic meters.
REQ.1.2.4	Mine Velocity	The system shall be able to determine the velocity of a moving mine (drifting) within .1 m/sec
REQ.1.2.5	Mine Path	The system shall be able to predict the position of a moving mine (drifting) within 10 sq. meters for a period of 30 minutes after detection.
REQ.2	Assess/Identify	The system shall assess the information to determine if threat is a mine and what type of mine.
REQ.2.1	Assess	The system shall assess the threat information to determine if threat is a mine.
REQ.2.1.1	Threat signature data comparison	The system shall compare gathered threat data to an existing data and determine whether or not a threat is a mine within xx seconds and with a 90% level of confidence
REQ.2.2	Identify	The system shall identify different types of underwater mines, drifting, moored, bottom/buried along with the fuse type of the mine.
REQ.2.2.1	Mine Classification	The system shall correctly differentiate between the types of mines (drifting, moored, and bottom/buried) with a 90% level of confidence
REQ.2.2.2	Mine Fuse Identification	The system shall correctly differentiate between contact and influence sensing fuses with a 90% level of confidence
REQ.3	Report	The system shall transmit all waterborne contacts with a threat assessment as well as system status in a real time format
REQ.3.1	Mine Threat Identification Report	The system shall transmit all identified mine data within 10 seconds of collection

ID	Requirement Name	Requirement
REQ.3.2	Non-Mine Threat Identification Report	The system shall transmit all identified non-mine data within 60 seconds of collection
REQ.3.3	Operational Status	The system will transmit operational status such as sonar sensor operational status, battery power level, and data storage level, every 10 minutes, or when queried by an operator
REQ.3.4	Mine Location Report	The system shall report mine location in the Geographic Coordinate System (i.e. lat-long-depth)
REQ.4	Suitability	The system shall be operationally suitable.
REQ.4.1	Operational Availability	The system shall have an operational availability of 0.9.
REQ.4.2	Maintainability	The system shall require no more than 10 days maintenance per fiscal year
REQ.4.2.1	Built in Test (BIT)	The system shall incorporate a Built-in-Test (BIT).
REQ.4.2.1.1	BIT Execution	The BIT shall execute automatically on power-up, following reset, and when initiated by an operator.
REQ.4.2.1.2	BIT Operation	The BIT shall be performed continuously to monitor MSDS unit operation including network/communications integrity.
REQ.4.2.1.3	BIT Errors	Any errors detected during start-up and BIT shall be alarmed and displayed for the operator
REQ.4.3	Reliability	The system shall have a Mean Time Between Failure (MTBF) of XX hours.
REQ.5	Physical Requirements	The system shall be fully compatible with the MH-60R/S CSTRS (Carriage, Stream, Tow, and Recover System)
REQ.5.1	Transportability	The system shall be able to be transported on current Navy vessels.

ID	Requirement Name	Requirement
REQ.5.2	Environmental Requirements	The system shall be capable of operating in ocean environments worldwide.
REQ.5.2.1	Temperature	The system shall be capable of meeting operation performance requirements in water temperatures between 0 deg C (32 deg F) and 49 deg C (120 deg F approx).
REQ.5.2.2	Water Salinity	The system shall be capable of operating in salt concentrations between zero and 70 grams per liter
REQ.5.2.3	Water Current	The system shall be capable of operating in water currents of up to 1 m/sec (approximately a 2 knot current)
REQ.5.2.4	Water Alkalinity	The system shall be capable of operating in water with pH levels between 6.8 and .78
REQ.6	Interoperability	The system shall be capable of transmitting sensing/identification data.
REQ.6.1	C4ISR Interoperability	The system shall be interoperable with existing Naval Command, Control, Computers and Communication Intelligence Surveillance and Reconnaissance (C4ISR) systems
REQ.7	Location Awareness	The system shall be capable of knowing its location within the Geographic Coordinate System (i.e. lat-long-depth) within 10 cubic meters
REQ.7.1	Awareness of other Vessels	The system shall be capable of knowing the Geographic Coordinate System (i.e. lat-long-depth) location of other fleet assets and non-fleet vessels within 1 mile.
REQ.8	Cooperative Search	The system shall be capable of adaptive and cooperative search with other organic and dedicated mine searching vessels and systems.

Table 10. MSDS Requirements Summary

B. FUNCTIONAL ANALYSIS

This section describes the MSDS functional breakdown, decomposition, and logical interactions and relationships of all system functions. The overall function is to conduct mine detection. In order to meet this task, the MSDS overall function is decomposed down to three main (top-level) functional elements:

- Search/Detect Threat
- Assess/Identify Threat
- Report Threat Information

The aforementioned three main functions are further subdivided into sub functions which are shown in the hierarchal diagrams (Figure 16 – Figure 19).

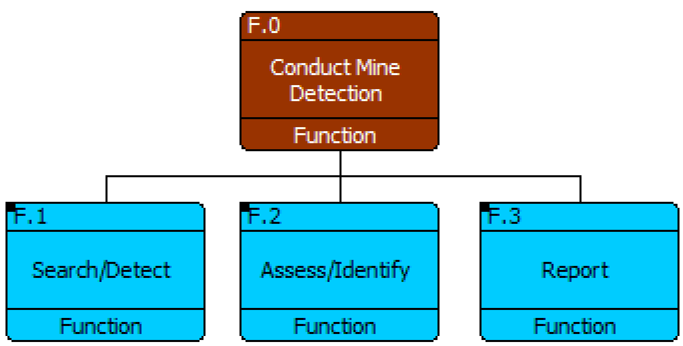

Figure 16. Hierarchy of Functions – Level 1, Function 0

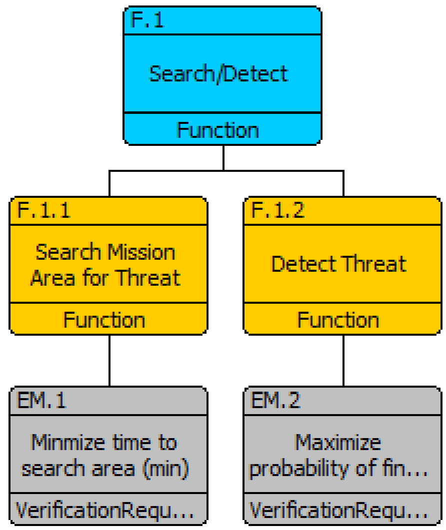

Figure 17. Hierarchy of Functions – Level 2 and EMs - Function 1.0

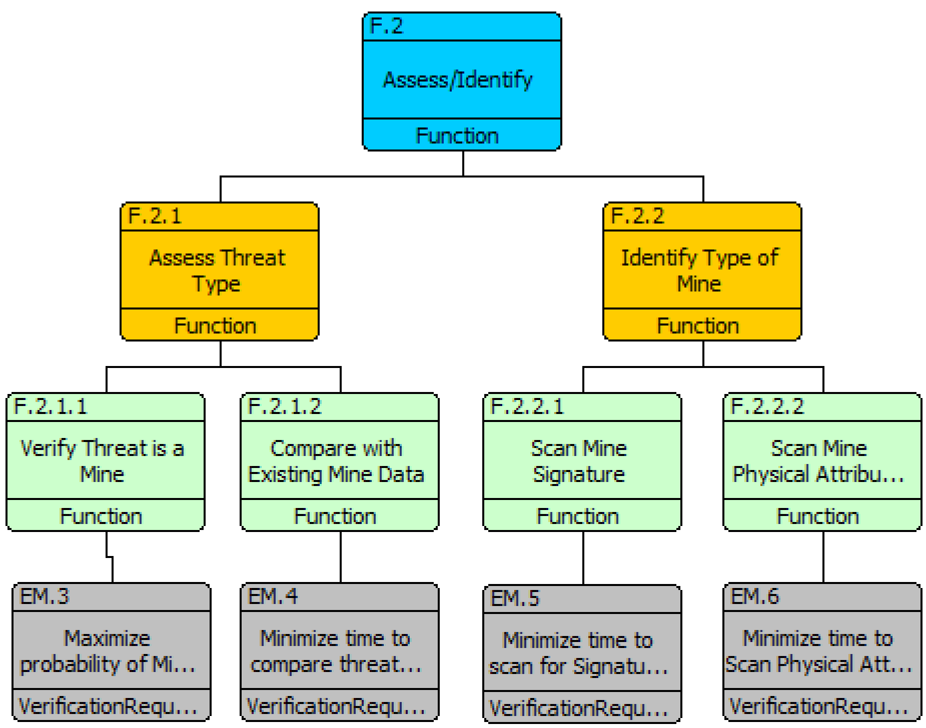

Figure 18. Hierarchy of Functions – Level 2, Level 3 and EMs Function 2.0

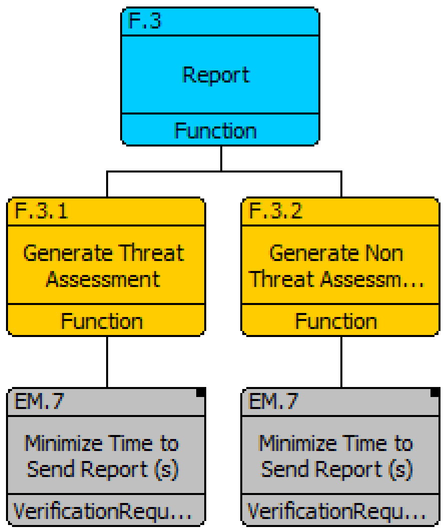

Figure 19. Hierarchy of Functions – Level 2 and EMs Function 3.0

Each of the above functions and sub functions are mapped directly/indirectly to a system functional requirement as shown in Table 11.

Function ID	Function	Requirement
F.1	Search/Detect	REQ.1 Search/Detect
F.1.1	Search Mission Area for Threat	REQ.1.1 Search Sensing REQ.1.1.1 Searching Speed
F.1.2	Detect Threat	REQ.1.2 Detect REQ.1.2.1 Mine Location REQ.1.2.2 Mine Depth REQ.1.2.3 Mine Coordinates REQ.1.2.4 Mine Velocity REQ.1.2.5 Mine Path
F.2	Assess/Identify	REQ.2 Assess/Identify
F.2.1	Assess Threat Type	REQ.2.1 Assess
F.2.1.1	Verify Threat is a Mine	REQ.2.1.1 Threat signature data comparison
F.2.1.2	Compare with Existing Mine Data	REQ.2.1.1 Threat signature data comparison
F.2.2	Identify Type of Mine	REQ.2.2 Identify
F.2.2.1	Scan Mine Signature	REQ.2.2.1 Mine Classification REQ.2.2.2 Mine Fuse Identification
F.2.2.2	Scan Mine Physical Attributes	REQ.2.2.1 Mine Classification REQ.2.2.2 Mine Fuse Identification
F.3	Report	REQ.3 Report REQ.3.3 Operational Status
F.3.1	Generate Threat Assessment	REQ.3.1 Mine Threat Identification Report REQ.3.4 Mine Location Report
F.3.2	Generate Non Threat Assessment	REQ.3.2 Non-Mine Threat Identification Report

Table 11. MSDS Functional Requirements Tracing

The System Engineering process has now been executed up to the System Architecting step of the left side of the VEE as shown earlier in Figure 3. Next, components of the U.S. Navy’s CONOPS will be compared to these decomposed functions by allocating them to fielded systems. This comparison will provide a fresh look at the CONOPS as a means to identify strengths, weaknesses, and improvement areas. This analysis is detailed in the following sections.

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V. OPERATIONAL ANALYSIS

The U.S. Navy will ultimately lead the effort to search the Strait of Hormuz for the presence of sea mines if and when that effort is needed. The CONOPS and the systems that support it will enable the Navy in this endeavor. In the operational analysis to follow, the capabilities of the Navy's current MCM CONOPS components are compared to the DRM established functional needs. By performing the comparison by allocation, specific inferences are made to identify aspects of the CONOPS for which improvement is needed. Lastly, the authors present their recommendations for possible ways in which the CONOPS could be strengthened for improvement as it is envisioned to be utilized within the context of the DRM.

A. MODULAR MCM CONOPS REQUIREMENTS OR CAPABILITIES

The mine detection portion of the U.S. Navy's organic in stride mine countermeasures CONOPS has been narrowed to the use of active sonar and electro-optical sensors in the form of streak tube imaging laser (STIL) and LIDAR. These technologies are employed by two systems that are both intended to be deployed in the future from the MH-60S helicopter. Active sonar and STIL will be provided by the AN/AQS-20A mine hunting system. LIDAR technology is relatively new and is provided by the Airborne Laser-Mine Detection System (AES-1 ALMDS). By using two systems, the water volume from the surface (or near surface) to the bottom of relatively shallow littoral waters can be effectively searched. The extent to which these two systems satisfy the functional needs of the Mine Detection Safety System is shown by an allocation comparison in Table 12. Only the highest level functions are shown.

Function	Solution
Search/Detect	AES-1 ALMDS (LIDAR at/near surface) AN/AQS-20A(depths in excess of 10 m)
Assess/Identify	AES-1 ALMDS (LIDAR at/near surface) AN/AQS-20A(depths in excess of 10 m)
Report	Operator function using data gathered by above systems
Generate Threat Assessment	Operator function using data gathered by above systems
Generate Non Threat Assessment	Operator function using data gathered by above systems

Table 12. Functional Allocation

The AN/AQS-20A mine hunting sonar is intended to replace the AN/AQS-24A sonar system as the work horse of the Navy's mine detection systems. Both the AN/AQS-24A and the AN/AQS-20A have been towed beneath the surface by the CH-53/MH-53 helicopters; The AN/AQS-20A is planned to be towed behind the newer MH-60S helicopters. The AN/AQS-20A utilizes five sonar sensors to "look down, out to the sides, and forward" for mines when towed beneath the surface or maintained at a fixed height above the ocean floor. Additionally, the electro-optical sensors enable the system to capture and transmit high resolution images of an object. The AN/AQS-20A is utilized to detect, locate, classify, and identify moored and bottom sea mines. Limitations of the AN/AQS-20A are the need to house special operating equipment as modifications to the MH-60S internal cabin space as well as the need for a dedicated operator on board the MH-60S during operation.

The AN/AQS-20A is ineffective for finding mines at the surface and the near surface. The AES-1 ALMDS system is utilized to search the area by using four cameras mounted beneath a separate MH-60S helicopter; the STIL capture images of the ocean surface that are illuminated (lit up) by a wide fan of pulsed blue-green laser light. The laser source and STIL (cameras) are mounted in a pod beneath the MH-60S airframe. The AES-1 ALMDS includes digital image software that employs a "…automatic target recognition algorithm to pick out potential mine-like objects, and stores their images for

classification by shipboard fleet operators, using computer-aided post-mission analysis tools." While this LIDAR system does not require a dedicated operator onboard the MH-60S helicopter, the need for operator evaluation in a post-mission analysis shipboard setting represents a significant limitation of not providing real time data. The AES-1 ALMDS system is intended to be used to detect surface and near surface floating and drifting mines.

B. CURRENT CONOPS REQUIRED CAPABILITY VERSUS MODELING RESULTS/INFERENCES

The mine detection modeling of the Strait of Hormuz has been performed to represent all mine detection efforts with active sonar. The model does not address the need for two separate technologies; one to identify mines near the surface, and a different one to detect mines that are moored beneath the surface or resting on the sea floor. All mine detection behavior simulates the use of active sonar techniques. LIDAR systems are the current preferred technology used to detect surface and near surface mines. For the purpose of this analysis, LIDAR has been assumed to be as capable of detecting surface and near surface mines as active sonar is of detecting subsurface and bottom mines. In spite of the limitations of the modeling approach, meaningful inferences can be drawn about the performance of the Navy's CONOPS.

Mine detection modeling of the Strait of Hormuz produced the following results:

- A minimum of approximately 1.4 days will be required to clear 95% of all of the sea mines from both sea lanes with a confidence level of 90%.
- A total of ten (10) sensor platforms (5 per sea lane) are required to operate simultaneously non-stop during that 1.4 day period.

These results represent challenges to the US Navy's organic modular MCM vision.

- A minimum of five LCS hulls would be required full time to perform the Airborne Mine Countermeasures mission (two Sikorsky CH-60/S helicopters deployed from each LCS).
- Each CH-60/S is capable of deploying either one AN/ALQ-20A mine hunting sonar system from a Carriage, Stream, Tow, and Recover System (CSTRS) or one AES-ALMDS (Airborne Laser Mine Detection System) from a standard BRU-14 bomb rack but not both simultaneously.

- The inability of one CH-60/S platform to search for moored and bottom mines using the AN/AQS-20A sonar and search for surface and near surface mines using the AES-1 ALMDS LIDAR essentially doubles the number of helicopters (and consequently, LCS hulls) needed regardless of the other missions that the helicopters will be required to conduct.

C. MCM CONOPS RECOMMENDATIONS

In response to the challenges identified from the Strait of Hormuz DRM., recommendations to revise or enhance the Navy's current MCM CONOPS are presented.

- A new MCM CONOPS should be created to address the resource limitations identified from the DRM study. This new MCM CONOPS would represent a near term solution by allocating or reassigning assets from other mission CONOPS or from programs currently planned for retirement. The current CONOPS calls for 55 LCS hulls. The near term absence of available hulls could be filled by the utilization of Arleigh Burke class destroyers as dedicated AMCM platforms capable of deploying two MH-60/S helicopters each. Alternatively, a shortage of MH-60/S helicopters could be mitigated by extending the life of older CH-53 helicopters from the larger LHA and LHD class ships. As part of the new CONOPS, the retirement of the dedicated Minesweeper fleet should be revisited.
- The development of a new MCM CONOPS must be fully analyzed far beyond the suggestions provided above. The time limitations of this effort have precluded a full analysis. As a minimum, the new MCM CONOPS must be developed and refined by successively repeating the evaluation performed.
- Incorporating automated MCM search, detection, identification, and assessment efforts is a study in and of itself and should be undertaken separately. Automation is needed to satisfy the effective need statement goal of getting the warfighter out of the minefield during MCM operations. Currently, warfighters fly the helicopters and operate helicopter crew cabin consoles as part of use of the AN/AQS-20A mine hunting sonar; these warfighters are essentially in the minefield when they are flying above it. Additionally, warfighters are key components of the data processing aspects of the threat assessment/identification functions as shown from the functional allocation of Table 12 for both active sonar and LIDAR. In the case of LIDAR use, operators are needed to evaluate images captured and recorded by the cameras as part of the threat identification and assessment process. Because the LIDAR (AN/AES-1 ALMDS) solution particularly addresses the surface and near surface depths where drifting mines are most prevalent, information processing delays introduce additional uncertainty to the outcome of subsequent efforts (i.e., acquisition and neutralization of moving targets such as drifting mines).

VI. CONCLUSIONS/FUTURE WORK

The project provides a “fresh look” at the current CONOPS intended to be served by the MCM Mission Modules under development for the LCS. Modeling techniques were applied to vet the current CONOPS in response to the mission of searching for and detecting sea mines placed in the Strait of Hormuz. The DRM developed can be used and expanded to enable the Navy’s MCM CONOPS effectiveness.

A. CONCLUSIONS

- The Strait of Hormuz provides an ideal and relevant setting for the evaluation of the performance of an MCM CONOPS. The elements of ocean environment including bottom depth profile, target signature parameters (oil tankers), and the characteristics of opposing force weapons (sea mines) have been combined to show how an enemy could leverage the interactions of these elements to achieve his stated goal of disrupting the flow of oil tanker traffic. By performing the effort to describe the tactics that could be used by the enemy, the capabilities that are needed to defeat them becomes the transparent goal of the exercise.
- Comparison of the search and detection functional requirements as derived from the Strait of Hormuz DRM to the U.S. Navy’s current MCM CONOPS components reveals the CONOPS to be both resource and technology limited. The CONOPS must be capable of detecting mines deployed at surface or near surface depths as well as mines deployed at deeper depths down to the ocean floor. The current CONOPS requires two systems (AN/AQS-20A active sonar and AN/AES-1 ALMDS LIDAR) to search these two depth ranges effectively. However, both systems are deployed from the same helicopter platform (MH-60/S). Because the two systems currently cannot be physically mounted on the air frame simultaneously, twice as many air frames are required to search at the two depth regions. This combined reliance upon two search technologies deployed from a common system reveals the effectiveness of the current CONOPS to be completely reliant upon the availability of MH-60/S helicopters. Lastly, the determination of the MH-60/S as the multi-mission helicopter of the CONOPS, the CONOPS ship platforms are not capable of deploying the larger AMCM helicopters (CH-53) which may be capable of physically mounting the two AMCM systems simultaneously.
- MCM search, detection, identification, and threat assessment activities must be less reliant upon human operators as integral information processors. The current Navy CONOPS rely heavily upon warfighters to fly the helicopters over the mine field, operate operator consoles in the cabin of the helicopter (in the case of the AN/AQS-20A), and to act as primary data evaluators for the

information gathered from both systems. The goal to get the warfighters out of the air above the minefield results from the effective need statement. Meeting this goal would additionally reduce the reliance upon the MH-60S helicopters freeing them to be available for the other CONOPS missions for which they are needed.

The above conclusions support the larger conclusion that a new CONOPS employing a combination of the older MCM platforms in conjunction with the new AMCM systems could achieve the same results with less uncertainty.

- The current CONOPS requires 55 LCS hulls each equipped with two MH-60/S helicopters.
- LCS production delays could be augmented through the utilization of Arleigh Burke class destroyers or amphibious assault ships (i.e., LHAs or LHDs) assuming enough MH-60/S helicopters were available.
- The larger CH-53 helicopters deployed from LHAs and LHDs could perform a portion of the AMCM mission, if the MH-60/S helicopters were not available in sufficient quantities.

B. FUTURE WORK

The Strait of Hormuz DRM has been developed as a basic tool for the evaluation of the Navy’s current CONOPS. Many simplifications have been employed in the performance simulation algorithms to the extent that it qualifies as a “back of the envelope” model. The modeling techniques could be evaluated to include suitability considerations such as operational availability due to scheduled and planned maintenance and AMCM system changeover times (e.g., removing the LIDAR and the bomb rack unit and replacing with the Carriage, Stream, Tow and Recovery System (CSTRS) and AN/AQS-20 sonar fish). Additionally, the assumption that the LIDAR performance in surface/near surface depths is represented by the sonar performance could be vetted by independently modeling LIDAR and incorporating if significantly different from sonar.

The Strait of Hormuz DRM also includes a modeling convenience of assigning identification and assessment results to mines as a function of their deployed depth. This convenience could be replaced by a more truthful representation of the identification and assessment functions by applying a probabilistic treatment to the prediction of those results.

Lastly with regard to the DRM modeling the environment could be expanded to study mine usage and detection in deeper water. Along with this, the mine inventory should be expanded to include active homing mines such as rising and vectoring variants. With the understanding that these sophisticated mines are almost solely developed to engage naval surface combatants, the potential target list would correspondingly be increased to include surface combatants.

Regardless of the complexity of the DRM performance model, the new MCM CONOPS should be developed and refined using the DRM performance as criteria. The relative comparison of the new verses the old CONOPS will provide meaningful insight into the relative strengths and weaknesses of the changes and support tradeoff study.

The mission capability of the MH-60/S to simultaneously carry AN/AQS-20A and AN/AES-1 ALMDS, and ultimately, simultaneously operate the two systems in flight to support AMCM missions is strongly encouraged. Because the "Achilles heel" of the current CONOPS is its reliance of AMCM systems deployed from the single MH-60/S helicopter combined with the need for the helicopter in support of other missions such as vertical replenishment, SAR, and CSAR, the operational availability of the helicopter should be increased to the maximum extent possible.

Finally, separate independent efforts are recommended to:

- develop automated MCM capabilities that do not insert warfighters into the minefield during MCM efforts.

And,

- elevate the human role of mine identification and assessment from required information processor to that of process performance manager.

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APPENDIX A – DRM MODEL METHODOLOGY

A. GENERATING THE PROBABILITY OF DETECTION (PD) TABLE

The Pd table is based on the Figure 10. This chart was recreated in Microsoft Excel as shown in Figure 20.

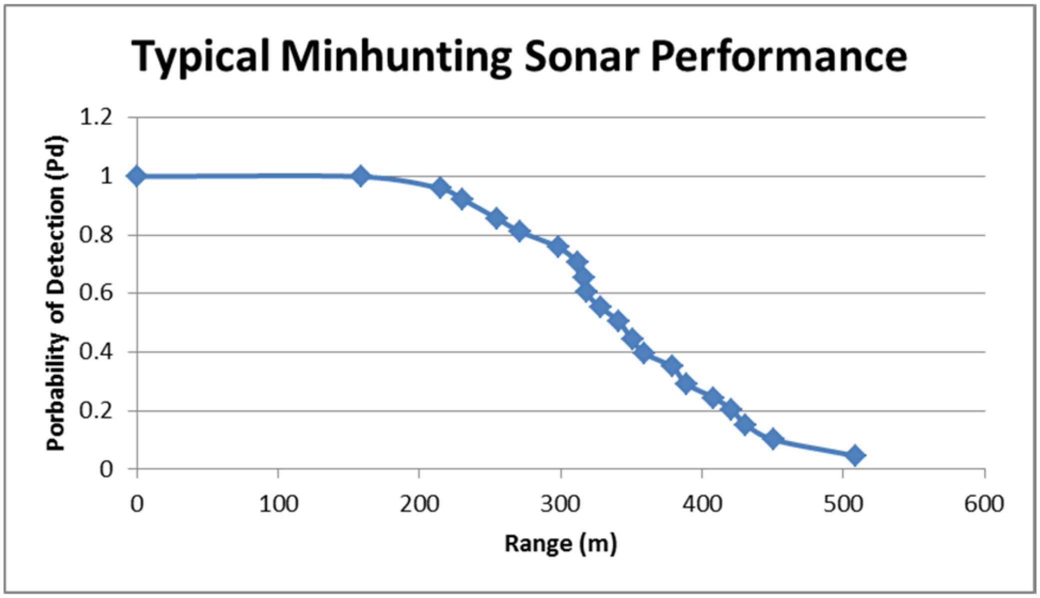

Figure 20. Pd Look Up Table

A lookup table was created from Figure 20 with the Pd corresponding to the mine to sensor range in Table 13.

Plot Point	Range (m)	P(det)
0	.0001	1
1	158	1.00
2	215	0.96
3	230	0.92
4	254	0.86
5	271	0.81
6	298	0.76
7	312	0.71
8	317	0.65
9	318	0.60
10	328	0.55
11	341	0.51
12	351	0.44
13	359	0.40
14	379	0.35
15	389	0.29
16	408	0.24
17	421	0.20
18	431	0.15
19	451	0.10
20	509	0.05

Table 13. SOH Search Time Summary

Since most mine to sensor ranges do not exactly fall on one of the ranges list in Table 13 an estimated Pd was calculated using a linear approximation.

$$y = m * x + y_0$$

Equation 2: Basic Linear Equation

$$m = \frac{y_2 - y_1}{x_2 - x_1} = \frac{Pd_2 - Pd_1}{R_2 - R_1}$$

Equation 3: Slope between two closest ranges

$$y_0 = y_2 - m * x_2$$
$$Pd_0 = Pd_2 - m * R_2$$

Equation 4: Calculating Y intercept

$$Pd = m * R + Pd_0$$

Equation 5: Final Pd equation

Equation 2 through Equation 5 show the simple calculations for performing linear approximations for Pd between two ranges in Table 13.

B. GENERATE MINE FIELD

Once the method for calculation Pd was complete the next step was to generate the mine field. The first 10 of the 500 mines used are shown in Table 14.

Mine Location			
Type of mine	**Depth of mine (m)**	**Loc_Width (m)**	**Loc_Length (m)**
M	55.0	1080.437	28235.6
M	51.0	816.420	28361.1
M	52.0	755.663	60247.7
B	88.0	974.473	20071.3
D	7.5	538.710	39115.9
B	88.0	992.843	5234.5
B	88.0	2495.274	44011.0
B	88.0	2542.438	31868.1
M	29.0	1576.185	49112.1
M	55.0	2889.577	9878.3

Table 14. Minefield Generation Example

The type of mine is assigned based on a random number compared to the P(Deployed) Mine Type on Table 4. Mine type uniform probability of deployment The depth of the mine is a uniform random distribution between the max. and min. depths shown in Table 5. Drifting and moored mine depth boundaries The mine location within the minefield is a uniform random distribution between 0 and the maximum length and width show in Table 3. Minefield Composition

C. SENSOR CALCULATIONS

Sensor 1 Location					
Depth of Sensor (m)	**Loc_Width (m)**	**Loc_Length (m)**	**Sensor Distance to Mine (m)**	**P(det)**	**Sensor 1 Detected Mine**
0.0	533.3	28235.6	549.862	4.980%	1
0.0	533.3	28361.1	287.644	77.896%	0
0.0	533.3	60247.7	228.330	92.654%	1
0.0	533.3	20071.3	449.832	10.408%	0
0.0	533.3	39115.9	9.195	99.994%	1
0.0	533.3	5234.5	467.861	8.518%	0
0.0	533.3	44011.0	1963.913	17.786%	0
0.0	533.3	31868.1	2011.031	18.213%	0
0.0	533.3	49112.1	1043.254	9.448%	0
0.0	533.3	9878.3	2356.886	21.345%	0

Table 15. Sensor Location Example

Table 15 shows the location of the sensor as it passes through the minefield. Depth of sensor was assumed to be zero. The location of the sensor was determined by evenly distributing the sensors across the minefield (Table 16).

	Depth of Sensor (m)	Loc_W (m)
Sensor 1	0	533
Sensor 2	0	1067
Sensor 3	0	1600
Sensor 4	0	2133
Sensor 5	0	2667

Table 16. Sensor Paths Through Minefield

The length location of the sensor is the same as the mine length. The assumption was that the highest probability of detection would occur when the mine-to-sensor distance was the smallest. Since the length values are the same the sensor-to-mine distance is calculated using only depth and width show in Equation 6 using the Pythagorean Theorem.

$$c = \sqrt{a^2 + b^2}$$
$$c = \sqrt{(width_{Mine} - width_{Sensor})^2 + (depth_{Mine} - depth_{Sensor})^2}$$

Equation 6: Sensor-to-Mine Distance Calculation

The probability of detection (Pd) was calculated using the method show in Equation 2 through Equation 5. The mine detection calculation was done using a binominal distribution with 1 trial, the P(detect) column value, and a random number generator.

$$Dection = BINOM.INV(trial, probablity, alpha)$$
$$Dection = BINOM.INV(1, < P(\det ect) >, RAND())$$

Equation 7: Mine Detection Calculation in Excel

The afore mentioned sensor calculation examples shown are for sensor 1. The process was repeated for the sensor 2 through 5. The overall mine detection calculation was a comparison of all the sensors. An individual mine was considered detected if at least one of the sensors detected it.

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